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IV

MOUNT OLGA

one of the landmarks in the Northern Territory of Australia, 200 miles south-west of Alice Springs.

These Mountains reach heights of about 2,600 feet above sea level; Ayers Rock 40 miles to the east, which measures six miles in circumference, rises in places almost vertically 1100 feet above the surrounding plains. They consist of conglomerates of Proterozoic age, believed by R. C. SPRIGG to be part of the widespread Sturtian Series of the Adelaide System. They are 'Inselberge' owing their preservation through several cycles of erosion to locally greater hardness. The bedding is almost vertical in Ayers Rock but gently dipping in Mt. Olga.

Photographs by Australian National Publicity Association, Melbourne.

EINLEITUNG

DIE GEOLOGISCHE ERFORSCHUNG DES AUSTRALISCHEN KONTINENTS UND SEINER RANDGEBIETE

Von M. F. GLAESSNER, *University of Adelaide*

Das Australien-Heft der Geologischen Rundschau will nicht mehr als einen Einblick in die Werkstatt der australischen Geologen sowie der Geophysiker und Ozeanographen Neuseelands geben. Die Grundlinien der Geologie dieses Großraumes können nicht im Rahmen einiger Arbeiten zusammenhängend dargelegt werden. Doch scheint es nützlich, kurz einige Hauptprobleme der Geologie Australiens und seiner Randgebiete zusammenfassend zu besprechen, in deren Rahmen die hier behandelten Einzelfragen fallen.

Geologische Beobachtungen wurden in Australien schon vor 160 Jahren gemacht, aber erst die Goldfunde seit 1850 führten zu eingehenden Forschungen. Die Erfordernisse des Bergbaus bestimmten dann maßgebend bis in die jüngste Zeit die Fragestellungen und die Schulung der australischen Geologen. Exakt-stratigraphische Arbeiten über die Sedimentärbecken, paläontologische Monographien und geotektonische Zusammenfassungen beginnen erst jetzt ihren rechtmäßigen Platz neben vorwiegend petrologischen und montangeologischen Arbeiten sowie eingehenden Beschreibungen einzelner Gebiete oder von Fossilfunden einzunehmen.

Die Kartierung des Landes liegt in den Händen der „Geological Surveys" der 6 Bundesstaaten (Westaustralien, Südaustralien, Victoria, Tasmanien, Neusüdwales, Queensland) und des „Bureau of Mineral Resources, Geology and Geophysics" in Canberra, das verfassungsgemäß nur in den bundeseigenen Gebieten, dem Gebiet der Bundeshauptstadt Canberra, dem „Northern Territory" und den „External Territories" auf eigene Initiative und dazu noch in einigen Staaten auf Grund von Vereinbarungen kartiert. Eine beträchtliche Anzahl von modernen geologischen Karten (meist im Maßstab 1 inch : 1 mile oder 1 : 63 360, 1 inch : 4 miles oder etwa 1 : 250 000, usw.) liegt schon vor, doch ist nur ein kleiner Teil des Staatsgebietes, meist in den dichter bevölkerten Randgebieten des Kontinents, im Detail geologisch aufgenommen. Seit 1953 gibt es eine „Geological Society of Australia", die jetzt über 500 Mitglieder zählt. Neun Universitäten haben geologisch-mineralogische Institute. Im Verhältnis zu der Größe des Gebietes, das etwa dem der Vereinigten Staaten (ausschließlich Alaska) gleicht, ist jedoch die Zahl der Geologen noch außerordentlich gering.

Etwa ein Sechstel des Gebietes wird von präkambrischen Gesteinen unterlagert. Daher nehmen heute Probleme des Präkambriums einen bedeutungsvollen Platz in geologischen Diskussionen ein. Die Entstehungs-

bedingungen präkambrischer Gesteine, z. B. der Charnockite [A. F. Wilson[1])], und Minerallagerstätten, z. B. Uran, Blei-Zinkerze, sedimentäre Eisenerze (Edwards) werden eingehend untersucht, daneben Fragen der Altersbestimmung mit Hilfe von radioaktiven Mineralien und des relativen Alters verschiedener Struktureinheiten und Intrusivkörper (Sprigg und R. B. Wilson, Carter). Die stratigraphische Gliederung des Präkambrium und die Fragen der Grenzziehung zwischen Archäikum, Proterozoikum und Paläozoikum stehen zur Diskussion. Das obere Proterozoikum ist in Südaustralien (Adelaide System) mehr als 10 km mächtig, tillit-führend und nicht metamorph in einer 750 km langen Faltenzone beispielgebend aufgeschlossen und erforscht (J. Geol. Soc. Aust. vol. 5, pt. 2, 1958). Schon lange hat man darin nach Fossilien gesucht, doch sind im australischen Präkambrium nur Stromatolithe einigermaßen häufig, abgesehen von einer außergewöhnlich interessanten Fauna in den höchsten Schichten, die aus Medusen und zahlreichen anderen unbeschalten Organismen besteht (Glaessner).

Die Stratigraphie des Kambrium und die Frage seiner Untergrenze und seiner Paläogeographie wurden kürzlich eingehend besprochen (20. Int. Geol. Congress, El Sistemo Cambrico, su Paleogeografia, y el Problema de su Base, vol. 2, pt. 2).

Die Stratigraphie und Fauna des Ordovizium, Silur, Devon und Perm wird untersucht, und viele paläontologische Arbeiten, besonders über Korallen, Bryozoen, Brachiopoden, Cephalopoden und andere Mollusken sowie Graptoliten, sind teils veröffentlicht, teils noch im Gange. Im Perm gibt es keine Fusulinen, doch wurden kürzlich die Kleinforaminiferen monographisch beschrieben. Das australische Perm mit seinen berühmten Vereisungsspuren, Glossopteris-Floren und reichen marinen Faunen trägt viel zur Kenntnis der Beziehungen zwischen den Kontinenten in dieser Periode bei (D. Hill, Teichert).

Die stratigraphische Untersuchung des australischen Mesozoikum und Tertiär gewinnt jetzt einen neuen Ansporn von der Erdölforschung und der damit verbundenen Anwendung mikropaläontologischer Methoden (Belford). Unsere Vorstellungen von den Sedimentärbildungen am Westrand des Kontinents haben sich grundlegend geändert (J. Geol. Soc. Aust., vol. 4, pt. 2, 1958). Am Südrand des Kontinents ist nicht nur das Miozän, sondern in verschiedenen Gebieten beinahe das gesamte Tertiär teils paralisch, teils marin entwickelt. Nur entlang der Ostküste fehlt das marine Tertiär vollkommen, so daß anzunehmen ist, daß sie erst nach dem Tertiär ihre heutige Lage eingenommen hat. Die Stratigraphie Neuguineas ist durch die Arbeiten der dort beschäftigten Erdölgeologen in großen Zügen aufgeklärt worden. Im Mesozoikum handelt es sich um den nördlichen Schelf des Australischen Kontinents und eine vorgelagerte Geosynklinalzone; im Tertiär bilden sich mehrere Teilgeosynklinalen und Inselbögen heraus. Es zeigen sich Beziehungen zu Ostindonesien, Australien

[1]) Die Autoren der im Australien-Heft der Geologischen Rundschau erscheinenden Arbeiten werden hier ohne Jahresangabe zitiert.

(besonders in der Mittelkreide) und Neukaledonien (besonders im Alttertiär).

Diese grundlegenden stratigraphischen Studien führen zu einer besseren Kenntnis der geotektonischen Gliederung des Kontinents. Die Existenz des australischen präkambrischen Schildes im Westen als einer zumindest seit dem Altpaläozoikum relativ stabilen Einheit ist allgemein bekannt; ihm steht im Osten das aus der paläozoischen Tasman-Geosynklinale entstandene Hochgebiet gegenüber. Entlang der Westküste und tief in den Schild eingreifend, kennen wir jetzt die großen Sedimentärbecken, die als tektonisch begrenzt angesehen werden. Auch die Südküste besitzt ein Randbecken (Eucla Basin), doch sind die Sedimentmächtigkeiten hier wesentlich geringer. Die Abgrenzung zwischen dem vor- bis altpaläozoischen Schild und der alt- bis jungpaläozoischen Geosynklinalzone im Osten bereitet Schwierigkeiten. Das Grenzgebiet besteht aus dem „Great Artesian Basin" im Norden und dem „Murray Basin" im Süden. Nahe der Oberfläche findet sich im Norden Kreide und im Süden Tertiär, doch zeigen neue Funde von marinen Sedimenten der mittleren Kreide im westlichen Teil des Murray-Beckens, daß es seit dem Mesozoikum eine Einheit mit dem Artesischen Becken bildete. Beide sind zum größten Teil tektonisch begrenzt, durch Aufwölbungen oder Bruchlinien, die alten Zügen der Tektonik des Kontinents folgen; ebenso scheint die junge Tektonik der Bekkenfüllung alte Strukturlinien des Untergrundes widerzuspiegeln. Die maximale E.-W.-Erstreckung des Großen Artesischen Beckens steht der des westaustralischen Schildes nicht nach.

Die Struktur der ostaustralischen Hochgebiete, die aus der Tasman-Geosynklinale entstanden sind, wird zumindest im Norden von parallelen alten Schwellen- und Beckenzonen beherrscht, die sich voneinander in Mächtigkeit und Fazies der Sedimente und in ihrem späteren tektonischen Verhalten unterscheiden. Die Hauptfaltungen folgen einander, wie schon lange bekannt ist, dem Alter nach von W nach E. In Victoria wird die mittel- bis oberdevonische Gebirgsbildung von Vulkanismus mit interessanten Caldera-Erscheinungen gefolgt (Hills). Diese und die folgende mittelkarbonische Faltung stabilisierte den größeren Teil der Tasman-Geosynklinalzone mit Ausnahme des Nordostgebietes, das im Oberperm zuletzt gefaltet wurde. Die Kreide, die im äußersten Osten an der Küste nördlich von Brisbane in beträchtlicher Mächtigkeit auftritt, ist noch einfach gefaltet, doch spricht das nicht für eine randliche „alpine" Faltungszone, da jetzt Faltungen des Mesozoikum und Tertiärs sowohl aus Südaustralien als auch aus dem zentralen Artesischen Becken bekannt sind. Die postpaläozoische Stabilität des östlichen Australien war eben nur relativ.

Zu einem Gürtel von mesozoischen und tertiären Falten von großer Bedeutung gelangt man erst im Randgebiet des Stillen Ozeans, dessen geotektonische Grenze jenseits von Neuseeland und Tonga von SSW nach NNE und von Fidschi gegen den Bismarck-Archipel von SE nach NW verläuft. Geologische, seismologische (Eiby) und ozeanographische (Brodie) Studien tragen viel zum Verständnis dieser zum großen Teil vom

Meer bedeckten Randzone bei. Bei dieser Erweiterung des australischen Kontinents nach E und NE handelt es sich nicht, wie früher oft irrtümlicherweise angenommen wurde, um ein versunkenes ehemaliges Kontinentalgebiet im geographischen Sinne, sondern um eine mobile geotektonische Randzone, deren verschiedene Teile oft in verschiedenem Sinne ihre relative Lage zum Meeresspiegel geändert haben. Ihre Mobilität wird von einem verhältnismäßig einfachen Netz von Leitlinien (Lineamenten) beherrscht, die sich in tektonisch besonders aktiven und kompliziert gebauten Gebieten überschneiden. Die bezeichnenden bogenförmigen und oft beinahe rechtwinkligen Änderungen der Faltungsrichtungen in diesem Gebiet sind als Übergänge von einer Leitlinie des Netzwerkes zu einer anderen zu verstehen. Nun hat sich in den letzten Jahren in zunehmendem Maße die Bedeutung solcher Lineament-Netzwerke für die Tektonik und Geomorphologie des gesamten Australischen Kontinents herausgestellt, was besonders von HILLS in einer Reihe von wichtigen Arbeiten nachgewiesen wurde. Es deutet vieles darauf hin, daß auch der Aufbau des jetzt größtenteils unter dem Meeresspiegel gelegenen Randgebietes von ähnlichen Lineamenten beherrscht wird. Diese Leitlinien scheinen auf einen sehr alten und dauernden Zustand der Erdkruste zurückzugehen, da sie die ältesten wie auch die jüngsten Strukturen, das tiefste wie auch das höchste Strukturniveau bestimmen. Kein Kontinent scheint sie deutlicher zu zeigen als Australien und seine Randgebiete, doch ist noch eine gewaltige Arbeit zu leisten, besonders in der Kartierung, um das, was wir heute zu erkennen glauben, auf eine gesicherte Grundlage zu stellen. Es scheint aber schon heute, daß von der geologischen Erkenntnis Australiens, die ursprünglich von rein europäischen Begriffen und Vorstellungen ausging, in Zukunft Beiträge von grundsätzlicher Bedeutung zur Frage der Natur und Entstehung der Kontinente zu erwarten sind.

THE CHARNOCKITIC ROCKS OF AUSTRALIA

by A. F. WILSON

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With 1 map (Fig. 1), 3 photographs (Fig. 2—4) and 1 Table

Abstract

A description of the structural environment and major rock types of each of the seven known areas of Australian charnockitic rocks is supported by representative chemical analyses (several of which are new). In some areas the whole terrain is dominantly of granulite metamorphic facies, but in other areas charnockitic rocks occur as relics set in rocks of amphibolite facies. The proximity of most areas to major faults suggests that the well-known texture of most charnockitic rocks may be due to either heat-transfer up deep-seated thrust-faults and plastic shear zones, or to slumping of blocks of the basement into hotter zones by normal faults.

Most Australian rocks with charnockitic affinities are metamorphic in origin. The basic rocks are mostly meta-igneous, many of which have suffered considerable metamorphic differentation. Intermediate and acid rocks are partly meta-igneous, but mostly are meta-sedimentary rocks or granitized basic granulites. Many rocks which are now charnockitic have suffered more than one metamorphism. Non-metamorphic acid orthopyroxenic rocks form important intrusions into the charnockitic rocks of Central Australia. These "magmas" were probably developed by palingenesis of metamorphosed rocks and in an environment deficient in oxygen.

I. Introduction

During 1955, I had the opportunity of visiting the classic areas of charnockitic rocks in India, and also spent some time in field studies of charnockitic rocks of Ceylon, Finland, Sweden, Scotland, and United States of America. In addition, thin-sections and specimens of charnockites from Africa, Greenland, and Antarctica have been seen.

In 1954 a review of the Australian charnockitic rocks was published, but in view of my experiences abroad some new points of view and changes in emphasis should now be brought forward.

II. Nomenclature

It would appear that the term "charnockite" has almost outlived its usefulness. By modern standards of nomenclature the original definition is unfortunate (although clear in its intent), and subsequent workers have so widened the use of the original term that petrographic chaos has resulted.

In 1900, "T. H. HOLLAND described a series of igneous rocks which are found at various localities in Madras and elsewhere in Southern India.

They are said to form a well-defined comagmatic region or petrographic province of Archaean age, the members of which range from a highly silicic hypersthene granite, through intermediate types, to norites and pyroxenites. HOLLAND gave the name "charnockite" to the granite, and proposed the designation "Charnockite Series" for the whole group, in order to distinguish the rocks of this petrographic province for survey purposes. He urged the importance of applying the terms only to the rocks of India" (WASHINGTON, 1916, p. 323). In HOLLAND's opinion the charnockite series is of igneous origin. Since 1900 rocks apparently indistinguishable chemically, mineralogically, and texturally, from the Indian rocks have been described from most of the Shield regions of the world, and to many of these the terms "charnockite" or "charnockitic" have been applied. Some of these extra-Indian rocks are claimed to be of igneous origin, but more and more workers (both in India and elsewhere) are now recognizing the essential metamorphic character of these rocks.

For detailed description of charnockitic rocks I prefer to use names such as "pyroxene granulite" (or better, "augite-hypersthene-andesine granulite"). For some rocks the terms "charnockitic granite" or "charnockoid granite" are useful in that they draw attention to the fact that some hypersthene granites show important similarities to HOLLAND's Madras charnockites.

Moreover, if the term "charnockite" is to be retained at all I prefer that the term "charnockitic suite" be used instead of "charnockite series" (see also GROVES in discussion of SUTTON and WATSON (1951, p. 298).

For the purpose of this paper, the following statement should suffice:

Rocks of the c h a r n o c k i t i c s u i t e are dark greasy bluish-grey or greenish-grey, medium-grained and coarse-grained rocks with xenomorphic texture ranging in composition from granite through norite to pyroxenite and characterized throughout by the presence of orthopyroxene. The charnockitic rocks appear much darker than would be expected from their mineral composition and this is "the main reason why even acid rocks of this series resemble basic varieties" (PICHAMUTHU, 1953, p. 8).

Most charnockitic rocks exhibit a more or less definite mineralogical banding. This is not readily recognizable on fresh hand-specimens such as are normally studied by petrographers in the laboratory. However, when seen in the field the charnockites when partly weathered exhibit banding which is often partly minutely contorted with a lineation (developed by crudely alined elongate hornblende or hypersthene crystals) parallel to the axes of the minute contortions. The banding of the charnockitic rocks has been considered by many of the earlier workers to be a sign of their igneous origin, but such rocks are more correctly designated gneisses or banded granulites. Their metamorphic character is now becoming more universally recognized. Moreover, when one considers them from the standpoint of metamorphic facies it becomes clear that the charnockitic rocks are co-facial with the country rocks (leptynites or gneisses) and properly may be placed within the granulite metamorphic facies as defined by ESKOLA (1939), TURNER (1951), and others.

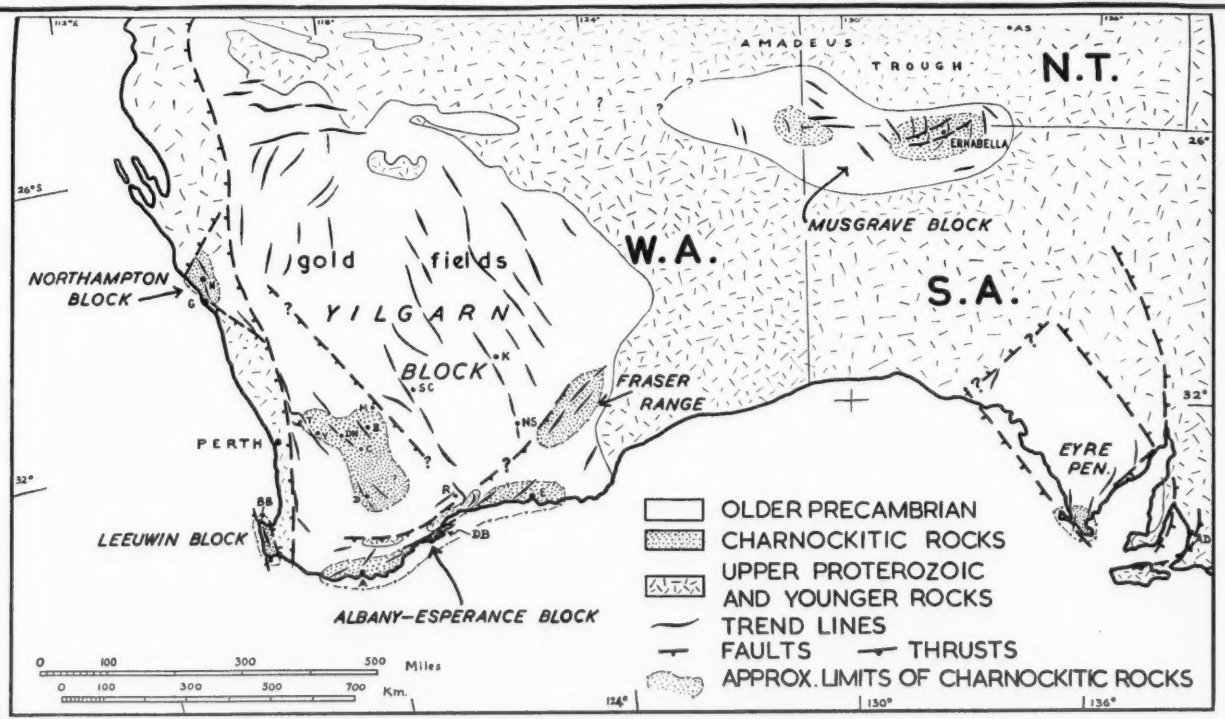

Fig. 1. The Charnockitic Rocks of Australia in their Tectonic Setting.
A = Albany, Ad = Adelaide, AS = Alice Springs, B = Bruce Rock, BB = Bunker Bay, C = Corrigin, D = Dumbleyung, DB = Doubtful Island Bay, DN = Dangin, E = Esperance, G = Geraldton, K = Kalgoorlie, M = Merredin, N = Northampton, NS = Norseman, N.T. = Northern Territory, R = Ravensthorpe, S.A. = South Australia, SC = Southern Cross, T = Toodyay, W.A. = Western Australia, Y = York.

III. General Structure

In Australia charnockitic rocks are confined to the Australian Pre-Cambrian Shield (see Fig. 1). They have been described in greatly-varying detail by TILLEY (1921) from Eyre Peninsula in South Australia; THOMSON (1911), FARQUHARSON (1917), MAITLAND (1924), AUROUSSEAU (1926), FLETCHER (1933), PRIDER (1945 a, 1945 b, 1948, 1954), LORD and GRAY (1951), WILSON (1952 b, 1954 b), from Western Australia; and WILSON (1947, 1950 a, 1950 b, 1952 b, 1953 b, 1954 a, 1954 b, 1954 c), and ROBINSON (1949) from Central Australia [1]).

As large areas of the Australian Shield are covered by laterite or sand, and much is geologically unexplored, it is impossible to delineate accurately the areas of charnockitic rocks. There are, however, several generalizations which may be made.

1. In Fig. 1 several areas are shown in which charnockitic rocks are found. In some of the areas (such as the Fraser Range) almost all rocks are of granulite metamorphic facies, but in others (such as the York District) the charnockitic rocks and other rocks of the granulite metamorphic facies occur as relics set in rocks of amphibolite facies.

2. Charnockitic rocks occur sporadically as large lenticular patches in the gneisses which flank the western, southern, and south-eastern portions of the vast Archaean goldfields regions in Western Australia. Within the goldfields themselves charnockites are unknown.

3. Charnockitic rocks are unknown north of the Trans-continental line running E.-W. through the Amadeus Trough in Central Australia. The only possible exception mentioned in the literature is the possibility that some of the basic gneisses and amphibolites of the Harts Range may be charnockitic (JOKLIK, 1955, p. 60).

4. Tectonic trends [2]) of the charnockitic rocks of Central Australia, Eyre Peninsula, and the western flank of the Australian Pre-Cambrian Shield usually lie between N.-S. and N.N.W. to S.S.E. This is remarkably similar to the trends within the non-charnockitic rocks of the Western Australian goldfields.

5. The tectonic trend of the gneisses and associated charnockitic rocks along the south coast of Western Australia (the Albany-Esperance Block) swings from an easterly trend west of Albany through E.N.E. to N.E. to Esperance (PRIDER, 1952, p. 146). This swing continues and takes in the Fraser Range with its N.E.- and N.N.E.-trending charnockites (WILSON, 1952 b, p. 222—223).

6. The gneisses and associated charnockites of the Albany-Esperance

[1]) Central Australia refers to the country near the geographic centre of the Continent, and includes large tracts of the States of South Australia, Western Australia, and the Northern Territory.

[2]) Unless otherwise stated, this refers to the trend indicated by a steeply-dipping foliation provided that the lineation due to mineral elongation, deep-seated dragfolds or other causes is consistent with the strike being the tectonic trend.

It has been found that random recordings of strike are unsatisfactory indicators of tectonic trend in charnockite areas (WILSON, 1953 b, 1954 a).

Block appear to be separated from the rocks of lower metamorphic facies of the Goldfields areas by large thrusts (Wilson, 1952 b, p. 222).

7. I have suggested that in the vicinity of Merredin a major fault separates the gneisses and associated charnockites to the west from the rocks of lower metamorphic facies in the goldfields areas to the east. Such a postulated tectonic break appears to trend N.N.W.-S.S.E. as shown in Fig. 1. One alternative suggestion, however, is that the distribution of the charnockitic and non-charnockitic rocks can be here accounted for by erosion to different levels of a series of N.N.W.-trending orogenic belts (Prider, 1952, p. 147).

8. The proximity of most Australian areas of charnockitic rocks to major faults (see Fig. 1) is significant. The granular texture (resembling a coarse pyroxene hornfels) of many of these rocks may be due mainly to either heat-transfer up deep-seated, thrust faults and plastic shear zones, or to slumping of blocks of basement into hotter zones by normal faults. The former is an attractive hypothesis for parts of the eastern Musgrave Block and Doubtful Island Bay region of the Albany-Esperance Block, whereas the latter is a preferred hypothesis for both the Northampton and Leeuwin Blocks.

9. The most significant minor structure of the Australian charnockitic rocks is the presence of small schlieren of quartzo-feldspathic material or mafic material. These are of variable size, ranging from a few millimetres in length through the common size of about 10 centimetres, up to several metres in length. These are isoclinally contorted, and the plunge of microfolds is fairly rigidly parallel for considerable distances, thus indicating reasonably constant orogenic diastrophic conditions during their formation. In the past, such minor folds have been overlooked because of the tendency for most workers to study the rocks in hand-specimen. It is on weathered surfaces that the true nature of the schlieren is recognizable. Linear elements of the rocks (hornblende and hypersthene crystals, streaks of quartz, etc.) are fairly rigidly oriented parallel to the axes of the folds in the schlieren. Many apparently homogeneous charnockitic rocks are found to contain the contorted schlieren when an outcrop is viewed looking "down-structure". This direction is readily determined by looking down the plunge of linear elements of the rock. This clear metamorphic imprint I have noticed in charnockitic rocks in most parts of the world, and is well developed in the type locality at Madras (see also Wilson, 1957; and Fig. 3 and 4).

IV. Occurrence and Environment of Australian Charnockites

A. Central Australia

The 'Musgrave Block' probably contains the largest tract of charnockitic rocks in Australia. Owing to its position in one of the most remote and arid portions of the Continent, most of the published geological information is of a reconnaissance nature obtained on expeditions, not bent primarily on geological research. Specimens of charnockitic rocks were accidently collec-

ted on most expeditions, but FARQUHARSON (in TALBOT et al., 1917, p. 130) was the first to call these rocks charnockites. STREICH (1893), BASEDOW (1905), and THOMSON (1911) recognized pyroxene granulites among the collections, and pointed out their similarity to the famous granulites of Saxony (WILSON, 1952 b, p. 206).

I have made four expeditions since 1943 to study the charnockitic rocks of this area. Several papers have been published, and final reports are now awaiting publication. Some of the most significant features of the charnockitic rocks of this areas are as follows: —

1. The oldest rocks are gneisses and granulites, many of which are of sedimentary origin. Some of these are khondalitic, and probable relict cross-bedding has been recognized in charnockitic granulites of granitic composition (WILSON, 1952 b, p. 208). The bulk of the gneisses are adamellitic or granodioritic in composition, and probably represented both original greywackes and primitive igneous rocks, all of which have now been subject to deep-seated regional metamorphism, which has been called plutonic metamorphism by several authors.

Some details of mineralogy and composition of representative rocks are set out in Table 1 (3, 4 and 11).

2. Interbedded with these rocks are contorted bands and lenses of basic charnockite. Some of these seem to represent relict basic sills or flows but for others a sedimentary origin is probable. Owing to the plastic deformation that the host rocks have obviously undergone in some areas some of the basic bands may have been discordant dykes, which now have been drawn into conformity during metamorphism. Examples of these rocks appear in Table 1 (12, 14, 19, 23, 25).

3. During the deep-seated regional metamorphism of the area some pyroxene granulites, which were being developed, suffered considerable granitization and migmatization and other metasomatic changes. This has resulted in most cases in the production of intermediate and acid charnockitic rocks from basic charnockites.

4. In considerable areas of the Musgrave Block the charnockitic rocks grade out into rocks of amphibolite metamorphic facies. A similar gradation in metamorphic facies has been recorded by RAMBERG in West Greenland.

5. Lineation is not as well developed in the charnockitic rocks as in those of amphibolite metamorphic facies. Nevertheless, preliminary microfabric studies seem to confirm the field evidence that the lineation due to mineral elongation is a b-lineation (WILSON, 1953 b, 1954 a).

6. Anorthosites and associated norites and pyroxenites occur as a large sill-like structure in the charnockitic gneisses. Little work has yet been done on this, excepting to show the remarkable constancy of composition of pyroxenes and feldspar throughout the whole sill-like structure. Plagioclase is andesine, about An 42, orthopyroxene about Of 35. These rocks, now called the Woodroffe norite group, have affinities with the (older) charnockitic gneisses (WILSON, 1952 b, p. 210).

7. The whole complex of charnockitic gneisses is injected by large masses of orthopyroxenic "granites" (mostly ferrohypersthene adamellites and granodiorites — see Table I, numbers 7, 8, and 10). One well-exposed mass, the Ernabella adamellite is about 24 miles long and 11 miles wide (see map, Wilson, 1947, and also 1954 c, vol. III). Contacts are usually sharp and locally discordant with corroded and sometimes angular unaltered xenoliths usually parallel to the contacts (Fig. 2).

Fig. 2. Sharp intrusive contact of the Ernabella (orthopyroxenic) adamellite and steeply-dipping charnockitic granulites. The adamellite contains a few dark bluish grey phenocrysts of plagioclase. 3/4 mile SW of summit of Mt. Carruthers, Musgrave Ranges, Central Australia.

Notwithstanding the presence of xenoliths (usually hornblende-sheathed pyroxene granulites, etc.) near the main contacts these granites are so massive that in most places away from the contacts reliable structural data rarely could be obtained. The general bluish dark greasy-grey "structureless" appearance of the rocks in handspecimen and in the field greatly hinders a macroscopic structural study.

These rocks are very interesting in that they are more like the type acid and intermediate charnockites of Madras than any others in Australia.

There is some petrographic evidence that the granites have been derived from the gneisses and granulites by metasomatism and recrystallization, but there is stronger field and petrographic evidence that the granites were magmatically emplaced. For instance, one of the major arguments for replacement origin of the granites (namely, the evidence of corrosion and replacement by K-feldspar of bent and poorly-twinned plagioclase

grains of the type usually found in the gneisses and granulites) is just as easily integrated into a hypothesis (which I prefer) that the pyroxene granites of this region were rheomorphic and magmatically emplaced. They differ in this respect from the Madras charnockites of comparable composition which I have seen in the field. The Madras rocks are metamorphic in origin.

The mineralogic and textural differences between the basement rocks and the granites are sufficiently significant to demand more than a simple explanation, namely the liberation of pyroxene and other minerals as relics of the basement in the granitization products, or as xenocrysts in the palingenetic magmatic product. Study of the mineralogic data on pp. 503—5 and in Table I will show that the pyroxenes of both rock groups are significantly different. The orthopyroxene, hornblende, etc. in the granites is consistently much more ferriferous than that of all types of the basement rocks. This increase in Fe^{++} in the orthopyroxene is not linked with either the SiO_2, alkali or total Fe content in the rocks concerned. The environment for generation of the pyroxenes and for the emplacement of the pyroxene granite magma (or crystal mush) was presumable critically deficient in oxygen.

Another difference is shown by the zircon suites. Recent work has suggested that a heterogeneous zircon suite may be made homogeneous during "ultrametamorphism of a grade higher than the sillimanite zone" (POLDERVAART and VON BACKSTRÖM, 1949, p. 467). If it is taken with the other known facts, the evidence of the homogeneous zircons tends to support a palingenetic source for the granites.

Present conclusions are that the orthopyroxenic granites were developed through deep-seated metasomatic reconstitution of the basement gneisses and granulites (probably already metamorphosed, and consisting in part of igneous rocks). The subsequent rheomorphic crystal mush (now magma) contained a considerable amount of interstitial "liquid", sufficiently rich in K and Si, and some "water", P and F to bring about the corrosion and replacement of early minerals so commonly seen.

B. Southern South Australia

In 1921 TILLEY showed that the gneissic complex of Southern Eyre Peninsula contains charnockitic rocks. Some of the granulites in this region are derived from calcareo-magnesic sediments of the Hutchison series, but most of the basic lenses in the Flinders gneiss are probably remnants of metamorphosed basic igneous rocks. The gneissic complex in Southern Eyre Peninsula is similar to that along the south coast of Western Australia (the Albany-Esperance Block) and that of the western flank of the Pre-Cambrian Shield. In all of these regions the host rocks are often non-charnockitic. This may be explained if the Flinders series, for instance, was developed by an alkali metasomatism taking place within the amphibolite facies rather than within the granulite (charnockite) facies (WILSON, 1952 b, p. 219—220).

C. Western Australia

Hypersthene-bearing granulites, identical with the typical Indian basic charnockites are not uncommon in the south-western and southern sections of Western Australia. The basic charnockites occur as lenticular bodies of greatly variable size, approximately ranging from a few millimetres in length through the common size of about 10 centimetres, up to several metres in length, set within acid gneiss. Some of these gneisses are hypersthene-bearing and resemble the acid charnockites of India, but most lack pyroxene and some belong to the amphibolite metamorphic facies. The basic charnockites are relics of a higher grade of metamorphism which once prevailed in this area.

1. York District

(1) Dangin: The most detailed study yet undertaken on the Western Australian charnockites was done by Prider at Dangin, 40 miles east of York. His paper (1945 b) is a notable contribution to the elucidation of the charnockite problem in general. The most important rocks are olivine hypersthenites, hornblende hypersthenites, hypersthene andesinites, plagioclase-hornblende-pyroxene granulites, garnet-biotite-cordierite-hypersthene rock and hypersthene-microperthite granite gneiss. While most of the rocks are remarkably similar to the Madras charnockites, the presence of olivine in the most basic rock at Dangin is a noteworthy feature. Prider's summary (1945 b, p. 171) concerning the Dangin charnockites is as follows: —

"This charnockitic suite is considered to be a series of basic intrusions into an older series of paraschists. It has, in places, been considerably contaminated by assimilation of the aluminous metasediments and in such cases is now represented by cordierite-bearing rocks. The basic charnockitic rocks and their contaminated equivalents have been subsequently invaded, under deep-seated conditions by granitic magma or emanations, and now appear as re-crystallized remnants of the original masses. They have suffered extensive granitization which has yielded the acid charnockites (hypersthene-alkali felspar gneisses) in which the hypersthene is considered to have been derived from the older hypersthene-bearing basic charnockites."

Some petrographic and chemical data appear in Table 1 (21 and 26).

(2) Toodyay:

a) The sedimentary character of certain coarsely-banded quartz-magnetite-hypersthene rocks (in which original bedding has been preserved in parallel trains of small magnetite grains included in the hypersthene) was first recognized by Prider (1944, pp. 115—117). The affinity of these iron-rich rocks with charnockites was not recognized at the time, but Prider's work led to a detailed study of jaspilites (banded iron formations) of Western Australia being undertaken by Miles (1946). He confirmed the sedimentary origin of the iron-rich rocks in the vicinity of York and Toodyay, and showed that they are the highly-metamorphosed equivalent of

the little-altered jaspilities of the goldfields areas of Western Australia. Some of the metamorphosed jaspilites described by MILES are very similar to certain of the charnockites, although this does not seem to have been recognized until my own work was commenced at Burges' Siding [see (3)].

b) Cordierite-anthophyllite rocks have been shown by PRIDER (1940) to be formed by metasomatism and metamorphism of spinel-olivine hypersthenites. Although the former assemblage is typical of a sub-facies of the amphibolite metamorphic facies, it is thought that the original hypersthenites are probably relics of a more extensive charnockitic assemblage. The charnockitic affinity of these rocks was not recognized, however, until PRIDER found similar ultrabasic rocks associated with typical charnockites at Dangin (PRIDER, 1945 b).

(3) Burges' Siding: Just south of Burges' Siding, six miles north of York, "metajaspilite and calc-silicate granulites of obvious sedimentary character are interbedded with garnet-sillimanite-cordierite rocks of pelitic origin. These are all interbedded with granitic gneisses, which seem to be migmatized greywackes and pelites. Certain facies of the metajaspilites and calc-silicate granulites cannot be distinguished in hand-specimen or in thin-section from basic charnockites" (WILSON, 1952 b, p. 216).

(4) Mt. Dick: At Mt. Dick, near Northam, basic charnockitic rocks have been mapped, but no detailed petrography has been carried out (LORD and GRAY, 1951).

(5) Corrigin and Bruce Rock: Basic charnockites have been discovered in these regions, and I have carried out preliminary studies, none of which has yet been published.

2. Dumbleyung

I recently discovered some very good examples of hypersthene-bearing pegmatitic schlieren replacing hypersthene granulites and hornblende-hypersthene granulites on the western shores of Lake Dumbleyung, near Wagin. Detailed work has not yet been done on this area.

3. Northampton Block

Garnet granulites have been recorded from this region for many years. PLAYFORD has recently given a short description of basic charnockites, which occur as irregular lenses in the coarse garnet- and sillimanite-bearing rocks of the Moonyoonooka district, near Geraldton (1952). The area is bounded by major faults and it seems to me to represent an area which has subsided to hotter zones. There is much evidence that these rocks have suffered more than one metamorphism.

4. Cape Leeuwin — Cape Naturaliste Region (Leeuwin Block)

CLARKE and PRIDER have mapped some parts of this area but the map and petrological report have not yet been published. However, PRIDER has compared the basic charnockite from Bunker Bay (first described by AUROUSSEAU (1926, p. 625) with the Dangin rocks, and in a personal

communication states that many of the basic lenses in the granitic gneisses of that region are charnockitic (see Table I, 22). As with the Northampton Block the area is apparently bounded by major faults. It may represent a slice of the mainland which earlier had subsided to hotter zones.

5. South Coast of Western Australia (Albany-Esperance Block)

Prider has recently briefly described large numbers of charnockitic rocks collected by Clarke and Phillipps from several points along the south coast. Prider has studied all of the available analyses of basic bands in the gneisses, and is of the opinion that their chemical composition indicates the close geochemical similarities of these basic granulites to basic igneous rocks (Clarke et al., 1954, p. 58). In this respect they are similar to basic lenses in the gneisses of the Toodyay region (Prider, 1944, p. 121) and Dangin (Prider, 1945 b, p. 169).

While I agree that many basic lenses of this area were original basic igneous rocks, I consider it probable that some are highly metasomatized and metamorphosed sediments. This is particularly so in the region near Fishery Cove in Doubtful Island Bay. The country rocks which enclose the basic lenses are often not of charnockitic character. In this respect they are similar to those of Southern Eyre Peninsula in South Australia, and the York district of Western Australia. Some chemical analyses of charnockites from the Albany-Esperance Block are set out in Table I (20, 24).

6. Fraser Range

Larcombe, in Maitland's report on geology in the vicinity of the Fraser Range (1924, p. 111) was the first to note the charnockitic character of some of the rocks of the Fraser Range. Large masses of remarkable homogeneous basic charnockites (in my opinion, the largest continuous outcrops of these rocks in Australia) are now known to occur in the Fraser Range (Wilson, 1952 b, p. 222). I have made a detailed study of two small selected areas, and full-scale mapping and laboratory work is contemplated in the near future. Some mineralogical and chemical data are set out in Table I (1, 17, 18).

Fig. 3 and 4 show the small contorted quartzo-felspathic schlieren, which are a feature of certain parts of the otherwise homogeneous basic charnockite. Were it not for these schlieren, the extensive areas of basic charnockite could easily be thought to have suffered little shearing during their metamorphism at the level of the granulite facies. Where lineation is observable in the field (exhibited by elongate hypersthene or rare hornblende crystals) it is found to be parallel to the axes of the micro-folds in the schlieren. It is my opinion that very considerable plastic flow has taken place in many parts of the Fraser Range, and identical phenomena have been seen by me in all other charnockite areas in Western Australia, as well as in India, Ceylon, Finland, and Sweden (see also Wilson, 1957).

In the Simon Hill region a garnet-pyroxene rock has been developed from basic charnockite by metasomatism. This rock is very similar to some

Fig. 3. Quartzo-feldspathic schlieren in basic charnockite. Large white patches (e.g. near the match box) are patches of lichen. Near Simon Hill, Fraser Range, Western Australia.

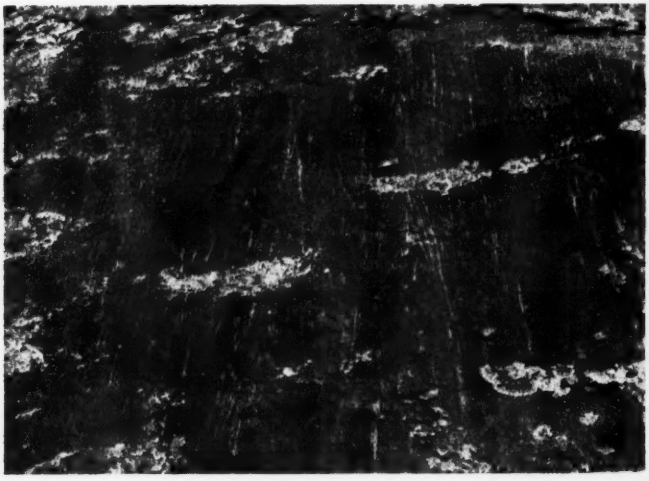

Fig. 4. Quartzo-feldspathic schlieren in basic charnockite. Same outcrop as Fig. 3, but viewed "down structure", i.e., down the weak lineation. Note that the sub-parallel schlieren of Fig. 3 are shown in Fig. 4 to be complexly folded. The lineation is parallel to the axes of the folds.

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TABLE 1

Chemical Analys

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
SiO_2	77.82	77.47	72.94	71.98	71.97	67.43	66.96	65.92	65.06	63.52	61.36	54.97	54.00	52.56	5
Al_2O_3	11.88	11.00	13.41	15.06	13.30	15.78	14.32	14.38	15.25	16.76	16.13	18.56	15.52	16.13	1
Fe_2O_3	0.24	1.04	0.67	1.16	1.29	1.63	1.78	1.81	3.06	0.96	2.84	2.54	3.97	0.90	
FeO	1.19	2.02	2.03	0.96	2.30	1.70	3.85	4.16	3.40	3.97	6.07	6.58	5.95	8.12	1
MgO	0.29	0.43	0.50	0.36	0.58	0.68	1.12	1.24	1.16	0.91	2.60	4.37	4.37	8.68	
CaO	0.56	1.02	2.02	2.74	2.10	2.33	2.06	3.23	2.88	4.51	4.12	8.20	7.11	10.02	1
Na_2O	2.06	2.86	2.38	2.76	2.78	3.80	2.73	3.33	4.01	3.88	3.07	2.73	4.36	2.44	
K_2O	5.45	4.14	4.94	4.40	4.24	5.86	5.14	4.16	3.96	4.01	2.23	0.52	1.53	0.38	
H_2O+	0.13	0.20	0.32	0.27	Nil	0.21	0.04	0.14	0.04	0.13	0.32	0.37	0.37	0.12	
H_2O-	Nil	0.05	0.06	0.05	0.27	0.19	0.18	0.16	0.20	0.06	0.13	0.04	0.20	0.08	
CO_2	Nil		Nil					Nil		Nil	tr	tr	0.25		
TiO_2	0.09	0.26	0.36	0.33	0.40	0.40	0.97	0.88	0.89	0.84	0.92	0.64	1.61	0.42	
P_2O_5	tr	nil	0.05	0.07	0.14	0.23	0.33	0.38	0.19	0.52	0.15	0.14	0.45	0.02	
MnO	0.06	nil	0.08	0.01	0.04	0.04	0.23	0.16		0.09	0.21	0.22	0.15	0.28	
BaO				0.19			0.16			0.12				tr	
S				0.03	0.05					0.11					
ZrO_2				0.05						0.08					
Cl										0.07					
	99.77	100.49	99.76	100.42	99.46	100.28	99.87	99.95	100.19	100.54	100.15	99.88	99.84	100.15	10

C.I.P.W. Norms

Q	42.15	41.22	34.04	32.41	33.60	17.64	24.12	21.05	18.24	14.12	18.81	9.96	2.99	0.06	
Or	32.25	24.46	28.91	26.13	25.02	34.47	30.02	24.58	23.35	23.80	13.34	2.78	9.05	2.22	
Ab	17.82	24.10	20.44	23.58	23.58	31.96	23.06	28.14	34.06	32.50	26.20	23.06	36.90	20.44	2
An	2.78	5.00	9.65	13.43	9.45	8.90	8.90	11.98	11.68	16.55	19.74	36.97	18.16	31.97	2
Cor	1.53		0.54	0.74	0.61		1.02				1.33				
Di Wo								0.64		0.93		1.16		7.42	
Di En						1.14		0.25	1.60	0.29		0.61	11.36	4.30	2
Di Fs								0.40		0.67		0.52		2.77	
Hy En	0.70	3.34	1.25	0.90	3.91	2.32	2.80	2.85	4.46	2.01	6.50	10.29	10.70	17.40	1
Hy Of	2.05		2.71	0.20			4.49	4.58		4.61	7.72	8.84		11.22	
Ol Fo															
Ol Fa															
Mt	0.35	1.62	0.93	1.62	1.86	2.32	2.55	2.62	4.41	1.39	4.18	3.71	5.75	1.39	
Il	0.15	0.61	0.68	0.61	0.76	0.76	1.82	1.67	1.67	1.52	1.75	1.22	3.04	0.76	
Pyr				0.06	0.12										
Ap			0.13	0.17	0.34	0.54	0.67	0.91	0.34	1.34	0.34	0.34	1.01	tr	
Zir				0.07						0.18			cal. =0.40		

Niggli Values

si	525.1	481.7	395.7	368.5			290.6	268.0		240.0	206.6	149.4		120.7	
al	47.37	40.2	42.60	45.33			36.45	34.37		37.4	31.92	29.69		21.76	
fm	11.33	19.3	16.10	11.06			27.87	27.71		20.6	38.18	38.50		47.66	
c	4.05	6.8	11.71	15.36			10.16	14.05		18.1	14.95	23.82		24.66	
alk	37.25	33.6	29.59	28.25			25.52	23.87		23.9	14.95	7.99		5.92	
ti	0.041	1.21	1.138	1.23			3.13	2.68		2.27	2.32	1.31		0.689	
k	0.630	0.49	0.571	0.511			0.55	0.45		0.41	0.324	0.102		0.093	
mg	0.250	0.21	0.253	0.25			0.26	0.27		0.25	0.344	0.462		0.627	
qz	276.1	247	177.3	155.5			87.5	72.5		44.4	46.8	17.4		—3.0	

Modes

Quartz	41	40	35.3	34.2	34.6	20.8	26	23	27.4	15	20.0	8.4	6.1		
K-feldspar	56	54	29.3	34.8	26.5	34.4	38	27	29.5	24	3.4		3.8	0.1	
Plagioclase			31.4	28.8	31.8	31.1	23	37	26.5	49	60.5	68.8	52.9	63.5	
(% An)			(35)	(35)	(33.4)	(33)	(29)	(34)		(39)	(35)	(48)	(33)	(56)	
Orthopyroxene		3	1.8		4.8	4.9	2	4	4.4	4	12.0	12.0	5.5	22.2	
(% Of)			(35)	(36)	(60.6)	(62.1)	(56)	(49)		(64)	(43)	(39)	(39)	(34)	
Clinopyroxene				1.2		2.1	3	3	2.2	2		5.6	13.7	12.0	
(% Wo)						(44)	(41)	(39)		(41)		(43)	(45)	(46)	
(% En)						(25)	(33)	(37)		(32)		(37)	(39)	(38)	
(% Fs)						(31)	(26)	(24)		(27)		(20)	(16)	(16)	
Hornblende				0.4		1.7	3	1	1.1	0.5			1.4	0.3	
Biotite		1	0.2			1.0	tr	tr		tr			7.9	0.1	
Iron Ores	0.5	2	1.7	0.5	2.1	3.4	4	4	7.9	3.5	4.1	5.2	1.6	1.7	
Apatite	tr		0.2		0.2	0.6	0.5	1	1.0	1.5			1.1	0.1	
Zircon	tr		0.1				0.3	tr		0.5					
Garnet	3														
S. G.		2.67			2.72	2.73			2.77		2.81	2.91	2.97		

1. No. 33 184. Garnetiferous acid granulite, near Simon Hill, Fraser Range, Western Australia. (Wilson, 1954 c, Vol. II, p. 339, Table V, 1.)
2. "Charnockite", St. Thomas' Mount, Madras, India. (Washington, 1916, p. 325.)
3. No. 30 829. Hypersthenic acid granulite, near Mt. Carruthers, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. II, p. 339, Table V, 3.)
4. No. 30 674. Hornblende-hypersthene-bearing acid granulite, 4 miles N.W. of Ernabella, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. II, p. 339, Table V, 7.)
5. "Charnockite", Trisul Hill, Meanambakam, Madras, India. (Howie, 1955, p. 732, Table I, 2.)
6. "Acid intermediate rock", Nambran Paramba, Tinnevelly district, Madras, India. (Howie, 1955, p. 732, Table I, 15.)
7. No. 30 558. Ferrohypersthene adamellite, Spinifex Hill, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. III, p. 158, Table V, 4.)
8. No. 30 385. Hypersthene adamellite, Ombagunda, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. III, p. 158, Table V, 6.)
9. "Intermediate rock", Miladampari, Palni Town, Madura, India. (Howie, 1955, p. 732, Table I, 17.)
10. No. 30 789. Ferrohypersthene granodiorite, Ernabella, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. III, p. 158, Table V, 10.)
11. No. 30 521. Hypersthene-quartz-andesine granulite, Inindi, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. II, p. 339, Table V, 17.)
12. No. 30 581. Quartz-augite-hypersthene-andesine granulite, Gilpin's Well, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. II, p. 340, Table VI, 25.)
13. "Intermediate rock", Salem, Madras, India. (Howie, 1955, p. 733, Table I, 20.)
14. No. 30 638. Salite-hypersthene-labradorite granulite, Taljaritja, Musgrave Ranges, Central Australia. (Wilson, 1954 c, Vol. II, p. 341, Table VII, 30.)
15. "Hy dia.
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al Analyses

14	15	16	17	18	19	20	21	22	23	24	25	26	27	
52.56	51.55	50.09	49.98	49.04	48.20	48.14	48.09	47.88	47.28	46.76	44.87	49.98	45.01	SiO_2
16.13	13.86	16.52	16.67	15.74	10.36	14.72	8.14	14.22	17.02	17.94	16.22	7.62	8.82	Al_2O_3
0.90	1.51	1.97	0.68	2.50	1.96	1.93	2.91	1.73	4.39	3.16	2.45	3.14	4.36	Fe_2O_3
8.12	11.63	11.35	11.16	12.13	9.09	12.92	12.40	12.36	7.88	8.78	13.39	7.78	12.38	FeO
8.68	5.80	5.88	7.64	6.52	16.91	6.78	14.50	6.35	8.62	6.84	7.58	25.81	19.90	MgO
10.02	10.28	9.03	9.22	9.27	10.32	10.53	10.47	10.23	10.54	10.22	9.84	4.62	7.28	CaO
2.44	3.08	2.64	1.87	1.56	0.88	2.26	0.92	2.47	2.23	2.97	1.74	0.53	0.17	Na_2O
0.38	0.54	0.51	0.78	0.57	0.39	0.35	0.46	0.51	0.56	1.46	0.29	0.20	0.02	K_2O
0.12	0.25	n.d.	0.18	0.14	0.26	0.68	0.72	0.23	0.29	0.64	0.26	0.13	0.02	H_2O+
0.08	0.12	0.06	0.34	Nil	0.28	Nil	0.03	0.07	0.04	0.04	0.24	0.11	0.21	H_2O-
			Nil	Nil	Nil	tr	0.10	Nil	tr	Nil	Nil			CO_2
0.42	1.12	1.49	1.19	1.92	0.97	1.44	0.79	2.95	0.70	0.93	2.56	0.17	1.32	TiO_2
0.02	0.23	0.35	0.09	0.52	0.04	0.19	0.11	0.40	0.09	0.23	0.43	tr	0.13	P_2O_5
0.28	0.23	0,45	0.26	0.36	0.37	0.24	0.57		0.21	0.18	0.32	0.20	0.22	MnO
tr														BaO
							FeS_2 = 0.01							
							Cr_2O_3 = 0.10							
							V_2O_3 = 0.25							
100.15	100.20	100.34	100.06	100.27	100.03	100.18	100.57	99.40	99.85	100.15	100.19	100.16	99.84	

W. Norms

0.06				3.60										Q	
2.22	3.02	2.78	5.00	3.34	2.22	1.67	2.73	2.78	3.34	8.90	1.72	1.11	1.16	Or	
20.44	26.00	22.53	16.24	13.10	7.34	18.86	7.76	20.96	18.34	17.29	14.67	4.72	1.42	Ab	
31.97	22.41	31.69	34.47	34.19	23.25	29.19	17.22	26.13	35.03	30.86	35.56	17.79	22.64	An	
										neph.= 4.26					
														Cor	
7.42			4.29	3.36	11.53				6.96		4.38			Di	Wo
4.30	22.72	8.79	2.10	1.60	7.93	18.50	27.58	20.26	4.42	15.46	2.15	3.95	10.04		En
2.77			2.11	1.72	2.65				2.09		2.15				Fs
17.40	17.94	28.01	14.30	14.70	18.20	17.84	26.31	15.16	7.95		9.37	47.09	37.51	Hy	En
11.22			13.86	15.84	6.08				3.76		9.36				Of
	2.92		1.89		11.32	7.33	11.93	5.60	6.39	15.82	5.21	19.50	17.79	Ol	Fo
			1.94		4.17				3.34		5.71				Fa
1.39	2.09	3.02	0.93	3.71	2.78	2.78	4.21	2.55	6.26	4.64	3.55	4.41	6.30	Mt	
0.76	2.16	2.89	2.28	3.65	1.82	2.74	1.50	5.62	1.37	1.82	4.86	0.30	2.49	Il	
							0.01							Pyr	
tr	0.54	1.01	0.34	1.34	0.10	0.34	0.27	1.01	0.24	0.34	1.01		0.30	Ap	
							Chromite = 0.16								
														Zir	

li Values

120.7			114.74	113.79	91.11			111.00	101.3		96.29			si
21.76			22.59	21.45	11.53			19.33	21.46		20.48			al
47.66			49.31	51.25	65.56			49.10	49.11		52.89			fm
24.66			22.59	22.98	20.87			25.31	24.16		22.63			c
5.92			5.51	4.32	2.04			6.26	5.27		4.00			alk
0.689			2.066	3.343	1.36			5.15	1.16		4.12			ti
0.093			0.225	0.194	0.222			0.11	0.146		0.10			k
0.627			0.533	0.646	0.732			0.45	0.563		0.461			mg
—3.0			—7.30	—3.49	—17.05				—19.8		—23.7			qz

odes

				0.1										Quartz
0.1			2.5	2.1										K-feldspar
63.5	45.0	43	53.5	52.1	17.1		16.0		52.1	50	45			Plagioclase
(56)	(38.7)				(91)	(50)	(73)		(59)	(50)	(60 to 72)			(% An)
22.2	25.2	11		24.6					13	10		69.7	56.4	Orthopyroxene
(34)	(56.5)		(44)	(53)	(26)	(52)	(38)		(34)		(35)	(27)	(24)	(% Of)
12.0	24.8	28	39.7	14.4	40.5				9	10			25.4	Clinopyroxene
(46)	(43)				(43)		48.4		(43)		(38) 36		(49)	(% Wo)
(38)	(32)				(44)				(39)		(31)		(41)	(% En)
(16)	(25)				(13)				(18)		(31)		(10)	(% Fs)
0.3	0.9	2			41.0		35.6		21.8	15		26.2	8.7	Hornblende
0.1										10				Biotite
1.7	3.7	15	4.1	5.6	1.3		nil		3.9		8	4.1	9.3	Iron Ores
0.1	0.4	1	0.2	1.0	0.1				0.2				0.2	Apatite
														Zircon
											11			Garnet
	3.10	3.16					3.28		3.07			3.26	3.43	S. G.

15. "Hypersthene diorite of charnockite series", Pallavarum, Madras, India. (HOWIE, 1955, p. 733, Table I, 23.)
16. "Hypersthene gabbro", St. Thomas' Mount, Madras, India. (C. RAJAGOPALAN, 1947, p. 238.)
17. No. 33 208. Pyroxene-plagioclase granulite, East Fraser Range, Western Australia. (WILSON, 1954 c, Vol. II, p. 341, Table VII, 37.)
18. No. 33 204. Pyroxene-plagioclase granulite, near Simon Hill, Fraser Range, Western Australia. (WILSON, 1954 c, Vol. II, p. 341, Table VII, 39.)
19. No. 30 230. Augite-anorthite-bronzite-hornblende rock, near Sentinel Hill, Musgrave Ranges, Central Australia. (WILSON, 1954 c, Vol. II, p. 341, Table VII, 40.)
20. "Plagioclase-hornblende-pyroxene granulite", Point Irby, South Coast, Western Australia. (CLARKE, et al., 1954, p. 38, Table IV, B.)
21. "Plagioclase-hornblende-pyroxene granulite", Dangin, Western Australia. (PRIDER, 1945 b, p. 161, Table V, 1.)
22. "Plagioclase-hornblende-pyroxene granulite", Bunker Bay, near Cape Naturaliste, Western Australia. (AUROUSSEAU, 1926, p. 625, but quoted from PICHAMUTHU, 1953, p. 168, No. 83.)
23. No. 30 639. Augite-hypersthene-hornblende-labradorite granulite, Taljaritja, Musgrave Ranges, Central Australia. (WILSON, 1954 c, Vol. II, p. 341, Table VII, 44.)
24. "Biotite-hornblende-pyroxene-plagioclase granulite", Cape Riche, South Coast, Western Australia. (CLARKE, et al., 1954, p. 38, Table IV, D.)
25. No. 30 543. Garnetized augite-hypersthene-labradorite granulite, near Red Ochre Well, Musgrave Ranges, Central Australia. (WILSON, 1954 c, Vol. II, p. 341, Table VII, 47.)
26. "Hornblende hypersthenite", Dangin, Western Australia. (PRIDER, 1945 b, p. 152, Table I, 1.)
27. "Pyroxenite", Pammal Hill, Pallavarsa, Madras, India. (HOWIE, 1955, p. 733, Table I, 31.)

Numbers (e.g. No. 33 184) refer to rock catalogue of University of Western Australia.

of those which are found with the khondalites of India. While I believe that most khondalites are the metamorphosed equivalents of pelitic sediments, the Fraser Range metasomatic rocks compel me to accept the possibility that some khondalites may be due to metasomatism in plastic shear zones. Since these are often sub-parallel to the bedding of isoclinally contorted rocks, it is easy to see how their possible metasomatic origin could be overlooked. Similar metasomatic processes have been described from other rocks and metamorphic facies (Wilson, 1953 a).

V. Mineralogy

The most detailed mineralogical work so far undertaken has been done by me on some Central Australian charnockitic rocks, but this is by no means complete. No chemical analyses of minerals (excepting feldspars — Wilson, 1950 a) has yet been undertaken. However, all available data are about to be published elsewhere. The scope of this paper allows the composition of only some of the major minerals to be included.

Since in Central Australia the charnockitic rocks fall into two divisions, namely (1) the gneisses and granulites of the basement complex, and (2) the intrusive granitic rocks, the general features of each group will be discussed separately.

1. Gneisses and Granulites

a) Quartz — Usually colourless, but often pale purple; commonly with inclusions of rutile or (?) haematite; often somewhat lenticular as in some Saxon and Finnish granulites; some granulites give orientation of quartz as rough girdle around lineation, which is // b.

b) K-feldspar — mostly non-twinned or poorly twinned microcline inverted from orthoclase (Wilson, 1950 a, p. 217 and 1950 b, p. 232); variably microperthitic (for analyses, see Wilson, 1950 a).

c) Plagioclase — the extreme composition range is oligoclase (An 26) in most acid rocks to anorthite (An 91) in an ultrabasic rock (determined optically by extinctions $\alpha' \wedge$ [010] in section $\perp$ a). For granulites of acid and intermediate composition andesine is the common plagioclase; in basic and ultrabasic rocks labradorite is usual. There are possibly some micro-antiperthites of exsolution origin but micro-antiperthites of replacement origin are very common.

d) Orthopyroxene — There is no large change in Fe/Mg ratio (shown in Table I as % Of) with change in colour index and silica content, but there is a tendency for the most ferriferous orthopyroxenes (commonly about Of 42) to occur in rocks in which plagioclase is near An 43, colour index near 30, and silica content about 60%. In more acid rocks the orthopyroxenes tend to become slightly less ferriferous (commonly Of 38) and more magnesic pyroxenes (extreme is Of 20) occur in more basic rocks. Changes in the orthopyroxenes are thus in the opposite direction for the acid rocks, but similar for ultrabasic rocks when compared with those of normal igneous complexes. Compositions were determined by measurement of R.I. (γ) (Poldervaart, 1950, p. 1076).

e) Clinopyroxene — Mostly calcic augites [determined optically by 2 V, and R.I. (β or γ) (Hess, 1949)]. As with the orthopyroxenes there is little change in any of the components (Wo, En, Fs), despite great changes in chemical composition of the host rock.

The relation between the composition of the clinopyroxene and that of the co-existing orthopyroxene is interesting. The tie-lines joining the pyroxene pairs consistently cut the Mg-Ca side-line at about 89 Ca instead of about 75 Ca, the figure pointed out by Hess (1941, p. 585, Fig. 11) as being usual for igneous rocks. The tie-lines for the pyroxenes of the associated igneous charnockitic rocks, however, consistently cut the Mg-Ca side-line at about 75 Ca which indicates that there is some fundamental difference between the pyroxenes of the intruded and intrusive charnockitic rocks in Central Australia. This matter is now being further studied with the aid of chemical analyses, and more specimens, including some from Scandinavia, Ceylon, and India.

f) Hornblende — Strongly pleochroic olive-green, brown, or reddish brown hornblende appears to be in metamorphic equilibrium with the pyroxenes in many charnockitic rocks, but particularly in the more basic types. In most quartz-bearing charnockitic granulites $\gamma = 1.674$ ($\pm$ 0.002) whereas in quartz-free rocks γ ranges from 1.674 to 1.686.

g) Mica — Muscovite is absent, but biotite occurs in many granulites. It is strongly pleochroic from pale fawn to brownish red, and $\beta = 1.629$. Some more intensive pleochroic biotites have $\beta = 1.641$.

h) Garnet — where garnet occurs (in khondalitic and kinzigitic rocks, and in some rocks as an alteration of pyroxene) it is always a pyrope-almandine low in manganese. A typical garnet has R.I. = 1.782 and MnO = 0.81%.

i) Apatite — (fluor-apatite, $\omega = 1.638$) is a common accessory.

j) Zircon — is a common accessory in all but the most basic granulites. In many rocks 3 or 4 types have been recognized, thus suggesting a sedimentary origin for such rocks. An early attempt was made to subdivide the rocks of the Musgrave Ranges on the basis of the variable fluorescence displayed by zircons (Wilson, 1947, p. 201, and 1950 b).

k) Scapolite — In one rock granules of scapolite (mizzonite, Me 76 with $\omega = 1.590$) appear to be in equilibrium with two pyroxenes, plagioclase and hornblende.

l) Sphene is absent.

2. The Intrusive Charnockitic Granites

a) Quartz — often bluish-grey in hand-specimen; some contain needles of rutile.

b) K-feldspar — mostly nontwinned microcline (after orthoclase); variably microperthitic; nonfluorescent (Wilson, 1950 b, p. 232).

c) Plagioclase — usually dark bluish-grey in hand-specimen and contains plentiful rutile inclusions); range in composition is An 29 in most acid, to An 40 in most basic granitic rocks but commonly An 37; micro-

antiperthite is not well-developed, and always seems to be of replacement rather than exsolution origin.

d) Orthopyroxene — the outstanding feature of these rocks is the very ferriferous nature of the pyroxenes (average about Of 55 with maximum Of 65). Pleochroism is not strong as shown by similar iron-rich pyroxenes from Varberg (Quensel, 1951, p. 248), Madras (Howie, 1955, p. 753) and other places.

e) Clinopyroxene — these are mostly calcic augites and are somewhat more ferriferous than those of granulites of comparable composition. The strange behaviour of the tie-lines of the co-existing pyroxenes of these rocks has been mentioned above (p. 504).

f) Amphibole — usually comprises about 1% of the orthopyroxenic intrusive rocks. Pleochroism is strong from pale fawn to greenish khaki. and γ ranges from 1.703 to 1.685, with higher values in more basic rocks.

g) Apatite — is an abundant accessory (1 to 1.5%) with $\omega = 1.635$ to 1.638.

h) Zircon — one type only is found in these rocks — this is in contrast with the basement gneisses and granulites. Its fluorescence (bright yellow or orange) has been used as an aid in mapping (Wilson, 1947, p. 201, and 1950 b).

i) Garnet and Sphene are absent, and biotite is rare.

VI. Some Conclusions

The following is a summary of the most significant contributions by Australian geologists to the study of charnockites and allied problems. Although many of the concepts are not new and some have been put forward with different emphasis by others [see excellent bibliography and summary by Pichamuthu (1953), Rama Rao (1945), and others] there is evidence in Australia for each of the following points [3]).

1. Isochemical metamorphism

Some charnockitic rocks, ranging from ultrabasic to acid types have been formed by (more or less) isochemical metamorphism under very deep-seated conditions of rocks of appropriate chemical composition. The possible structural mechanisms for placing the rocks in such an environment are suggested under "General Structure, 8".

a) Some were siliceous sediments which may even exhibit current-bedding (Wilson, 1947, p. 200; 1952 b, p. 208); others were banded iron formations or calc-sediments of various types (Wilson, 1952 b, p. 216; Tilley, 1921).

b) Some were dolerite dykes, sills, or basic lava flows (Tilley, 1921; Prider, 1945 b, p. 171; 1954 a, p. 58; Wilson, 1954 c, vol. II, pp. 279, 314).

c) Some were already metamorphosed rocks before the "charnockitic imprint" was placed upon them.

[3]) Some of these are recast from an earlier statement (Wilson, 1954 b, pp. 14 to 16). The absence of a reference indicates that I am about to amplify the point in another paper.

d) Some were portions of granite masses of the basement.

e) Some were ultrabasic intrusions, which may, or may not, have assimilated aluminous sediments during emplacement (PRIDER, 1940; 1945 b).

2. Granitization

Some acid and intermediate charnockitic rocks have been formed by the extensive granitization of basic and ultrabasic charnockites (PRIDER, 1945 b, p. 171; WILSON, 1952 b, p. 221).

a) If granitization takes place under granulite (or charnockite) grade of metamorphism the pyroxene in the acid and intermediate charnockites so formed will be derived as "resicrysts" from the disintegrated basic charnockite (PRIDER, 1945 b, p. 171; WILSON, 1952 b, p. 221) — but note that there may be a completely reconstructed orthopyroxene if there are marked changes in chemical and physical environment.

b) If granitization or migmatization takes place when the area is no longer subject to granulite (or charnockite) grade of metamorphism, the intermediate and acid rocks which enclose the basic charnockite lenses are no longer truly charnockitic. They are largely hornblende- or biotite-bearing, and the potash feldspar is often microcline instead of orthoclase. Any hypersthene which may have survived is usually rimmed with common hornblende or biotite (WILSON, 1952 b, p. 221).

3. Khondalites

Although most khondalites are probably the products of (more or less) isochemical metamorphism of certain sediments or meta-sediments, some may be developed from basic charnockites or other rocks by metasomatism (either by influx of Al, etc., or by subtraction of certain components thus leaving behind the more "refractory" elements. The garnets in many basic charnockites are found to have a metasomatic origin (WILSON, 1954 c, vol. II, p. 306).

4. Metasomatic hypersthene

a) Pegmatitic schlieren rich in hypersthene are commonly found replacing hornblende, biotite or iron ores in hornblende-rich gneisses and granulites. The presence of hypersthene rather than hornblende in these pegmatites is not due to an anhydrous environment, but rather to slight yet critical changes in the vapour pressures of "water" and possibly oxygen. Moreover, small variations in the Ca-femic components of the rock probably play an important role (WILSON, 1954 c, vol. II, p. 303).

b) Contamination of magma by alumina may give rise to hypersthene in either the magma itself (as has often been observed, e.g. WILSON, 1952 c, p. 82) or in the wallrocks where it replaces the femic minerals (WILSON, 1952 a, p. 636).

5. Metamorphic differentation

a) The "sweating out" of some components into favourable structural and physical environments commonly leads to development of schlieren of hypersthene, diopside, hornblende, garnet, and other minerals. The

formation of small lenses of pyroxenite and hornblendite may also be due primarily to calcium-rich emanations related to nearby alkali-metasomatism of basic schists; and secondarily to miniature "basic fronts" in that femic elements were in turn expelled during calcium metasomatism. Some of the ultrabasic charnockites (e.g., the "bahiaites") may owe certain of their unusual characters to such phenomena (Wilson, 1953 a, p. 100).

6. Micro-antiperthite is common in the charnockites of the basement gneisses and granulites, as well as in the magmatic pyroxene granites. Some are probably of exsolution origin, but the majority are excellent examples of replacement origin (Wilson, 1954 c, vol. II, pp. 228, 315; and vol. III, p. 165).

7. Fabric

a) Some charnockitic rocks have the fabric of a coarse hornfels, thus suggesting a (dominantly) thermal metamorphism. This may be caused by a downwarping of an area of crystalline rocks, whereby rocks already metamorphosed receive another metamorphic imprint. The anhydrous character of many of the resultant rocks may be partly due to the fact that the rocks to be metamorphosed are "dry", for the sediments have lost most of their original connate and loosely-combined water.

b) Some charnockitic rocks are b-tectonites, especially those pyroxene granulites which are the end-stage of regional metamorphism through the amphibolite facies. Lineation (shown as elongate crystals or aggregates of hypersthene, hornblende, quartz, etc.) is commonly parallel to axes of minor and major tight folds, and is useful as a mapping aid (Wilson, 1953 b, 1954 a).

8. Magmatic charnockites

Considerable areas of non-foliated orthopyroxene granites (mostly ferrohypersthene adamellites) are magmatically-emplaced masses of palingenetic origin. They have not been subsequently metamorphosed. The orthopyroxene and hornblende are more ferriferous than those of any of the injected charnockitic gneissic basement. Their environment of formation apparently was deficient in oxygen (Wilson, 1954 b, p. 15).

9. Most Australian rocks with charnockitic affinities are metamorphic in origin. The basic rocks are mostly meta-igneous rocks, many of which have suffered considerable metamorphic differentiation. Intermediate and acid rocks are partly meta-igneous, but mostly are meta-sedimentary rocks or granitized basic granulites. Many rocks which are now charnockites have suffered more than one metamorphism. Non-metamorphic acid orthopyroxenic rocks form important intrusive masses in Central Australia, but are unknown elsewhere in Australia.

Addendum

Since this paper was written (1956) extensive field work in Western Australia has considerably widened our knowledge of the distribution and structure of the charnockitic terrains.

A recent article (containing a map of all known charnockitic rocks in their tectonic setting) suggests that the charnockitic rocks in south-western Australia have been formed in four ways, namely (1) re-metamorphism of the thin Archaean crust beneath the troughs in which Archaean jaspilites, spilites, tuffs and erosion sediments were being deposited; (2) appropriate metamorphism of the keel of such troughs; (3) appropriate thermal metamorphism of the basement complex by injection of mobilized masses of down-warped basement complex; (4) thermal metamorphism (on a regional scale) of blocks of basement complex faulted into hot zones. Charnockitic rocks of early Archaean and late Archaean age are recognized. (WILSON, A. F., 1958: Advances in the knowledge of the structure and petrology of the Precambrian rocks of south-western Australia. Journ. Royal Soc. W. Aust., vol. 41, pp. 57—83.)

VII. Bibliography

AUROUSSEAU, M., 1926: Analyses of Three Australian Rocks. Proc. Linnaean Soc., New South Wales, vol. 51, pp. 614—626. — BASEDOW, H., 1905: Geological report on the country traversed by the South Australian Government North-West Prospecting Expedition, 1903. Trans. Royal Soc. S. Aust., vol. 29, pp. 57—102. – 1914: Journal of the Government North-West Expedition. Royal Geograph. Soc. Australasia (S.A. Branch). Adelaide. — CLARKE, E. DE C., PHILLIPPS, H. T., and PRIDER, R. T., 1954: The Pre-Cambrian of part of the South Coast of Western Australia. Journ. Royal Soc. W. Aust., vol. 38, pp. 1—64. — ESKOLA, P., 1939: Die metamorphen Gesteine, in Barth, Correns and Eskola: Die Entstehung der Gesteine. Julius Springer, Berlin, pp. 263—407. — FARQUHARSON, R. A., 1917: See Talbot et al., 1917. — FLETCHER, R. W., 1933: Metamorphic rocks of the Albany District, Western Australia (MS., University of Western Australia, Dept. of Geology Library). — HESS, H. H., 1941: Pyroxenes of common mafic magmas. Part 2, Amer. Mineral., vol. 26, no. 10, pp. 573—594. – 1949: Chemical composition and optical properties of common clinopyroxenes. Part 1, Amer. Mineral, vol. 34, pp. 621—666. — HOLLAND, T. H., 1900: The charnockite series, a group of Archaean hypersthenic rocks in Peninsular India. Mem. Geol. Surv. India, vol. 28. — HOWIE, R. A., 1955: The geochemistry of the charnockite series of Madras, India. Trans. Royal Soc. Edinburgh, vol. 62, part 3, pp. 725—768. — JOKLIK, G. F., 1955: The geology and mica-fields of the Harts Ranges, Central Australia. Bureau Min. Resources Australia, Bull. 26. — LARCOMBE, C. O. G., 1924: See Maitland (1924). — LORD, J. H., and GRAY, N. M., 1951: Report on examination of the iron deposit at Mt. Dick near Northam, Western Australia. Report Geol. Surv. W. Aust. for 1949, pp. 33—35. — MAITLAND, A. GIBB, 1925: Notes on the country in the vicinity of and to the northward of Israelite Bay, Eucla Division (petrology by C. O. G. Larcombe), Geol. Surv. W. Aust. Annual Prog. Report for 1924. — MILES K. R., 1946: Metamorphism of the Jasper Bars of Western Australia. Quart. Journ. Geol. Soc., vol. 102, pp. 115—155. — PICHAMUTHU, C. S., 1953: The charnockite problem. Mysore Geologists' Assoc., Bangalore, India. — PLAYFORD, P. E., 1952: Jurassic stratigraphy of the Geraldton area (MS., University of Western Australia, Dept. of Geology Library). — POLDERVAART, A., 1950: Correlation of physical properties and chemical composition in the plagioclase, olivine and orthopyroxene series. Amer. Mineral, vol. 35, pp. 1067—1079. — POLDERVAART, A., and VON BACK-

ström, J. W., 1949: A study of an area at Kakamas (Cape Province). Trans. Geol. Soc. South Africa, vol. 52, pp. 433—495. — Prider, R. T., 1940: Cordierite-anthophyllite rocks associated with spinel-hypersthenites from Toodyay, Western Australia. Geol. Mag., vol. 77, pp. 364—382. – 1944: The petrology of part of the Toodyay District. Journ. Royal Soc. W. Aust., vol. 28, pp. 83—137. – 1945 a: Sapphirine from Dangin, Western Australia. Geol. Mag., vol. 82, pp. 49—54. – 1945 b: Charnockitic and associated cordierite-bearing rocks from Dangin, Western Australia. Geol. Mag., vol. 82, pp. 145—172. – 1948: Igneous activity, metamorphism and ore formation in Western Australia. Journ. Royal Soc. W. Aust., vol. 31, pp. 43—84. – 1952: South-West Yilgarnia. Sir D. Mawson Anniversary Volume, Univ. of Adelaide, pp. 143—152. – 1954 a (with Clarke and Phillipps): See Clarke (1954). – 1954 b: The Pre-Cambrian succession in Western Australia. Proc. Pan Indian Ocean Science Congress, Perth, 1954, Sec. C, pp. 69—78. — Quensel, P., 1951: The charnockite series of the Varberg district on the south-western coast of Sweden. Arkiv för Mineral. och. Geol., Band nr. 10, pp. 227—332. — Rajagopalan, C., 1947: Studies in charnockites from St. Thomas' Mount, Madras. Part II, Proc. Indian Acad. Science, vol. 26, p. 237. — Rama Rao, B., 1945: The charnockite series of Mysore (Southern India). Mysore Geol. Dept., Bull. 18. — Robinson, E. G., 1949: The petrological nature of some rocks from the Mann, Tomkinson and Ayers Ranges of Central Australia. Trans. Royal Soc. S. Aust., vol. 73, pp. 29—39. — Streich, V., 1893: The country between the Everard Ranges and Barrow Range, etc. Trans. Royal Soc. S. Aust., vol. 16, pp. 74—115. — Sutton, J., and Watson, J., 1951: The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the North-West Highlands, and its bearings on the chronological classification of the Lewisian. Quart. Journ. Geol. Soc., vol. 106, pp. 241—296. — Talbot, H. W. B., and Clarke, E. de C. (with petrology by Farquharson, R. A.), 1917: A geological reconnaissance of the country between Laverton and the South Australian border, etc. Geol. Surv. West. Aust., Bull. 75. — Thomson, J. A., 1911: On rock specimens from Central and Western Australia. Journ. Royal Soc. New South Wales, vol. 45, pp. 292—317. — Tilley, C. E., 1921: The granite gneisses of Southern Eyre Peninsula (South Australia) and their associated amphibolites. Quart. Journ. Geol. Soc., vol. 77, pp. 75—134. — Turner, F. J., and Verhoogen, J., 1951: Igneous and metamorphic petrology. McGraw Hill, New York. — Washington, H. S., 1916: The charnockite series of igneous rocks. Amer. Journ. Science, 4th Series, vol. 41, pp. 323—338. — Wilson, A. F., 1947: The charnockites and associated rocks of North-Western South Australia. Pt. I. The Musgrave Ranges, Trans. Royal Soc. S. Aust., vol. 71, pp. 195—211. – 1948: Idem. Pt. 2. Dolerites from the Musgrave and Everard Ranges. Trans. Royal Soc. S. Aust., vol. 72, pp. 178—200. – 1950 a: Some unusual alkali-felspars in the Central Australian charnockitic rocks. Mineral Mag., vol. 29, pp. 215—224. – 1950 b: Fluorescent felspar and zircon as petrological aids. Mineral Mag., vol. 29, pp. 225—233. – 1952 a: Occurrence of metasomatic hypersthene, and its petrogenetic significance. Amer. Mineral, vol. 37, pp. 633—636. – 1952 b: The charnockite problem in Australia. Sir D. Mawson Anniversary Volume, Univ. of Adelaide, pp. 203—224. – 1952 c: Metamorphism of granite rocks by olivine dolerite in Central Australia. Geol. Mag., vol. 89, pp. 73—86. – 1953 a: Diopsidization and hornblendization — important metasomatic phenomena in the basic schists near Southern Cross, Western Australia. Journ. Royal Soc. W. Aust., vol. 37, pp. 97—103. – 1953 b: The Significance of lineation in Central Australia. Aust. Journ. Science, vol. 16, pp. 47—50. – 1954 a: The significance of lineation in Central Australia — a reply. Australian Journ. Science., vol. 16, pp. 242—243.

– 1954 b: Charnockitic rocks in Australia — a review. Proc. Pan Indian Ocean Science Congress, Perth, 1954, Sec. C, pp. 10—17. – 1954 c: Studies on Australian charnockitic rocks and related problems: — Vol. II: The charnockitic granulites and associated gneisses of Musgrave Ranges, Central Australia. Vol. III: The charnockitic granites and associated granites of Central Australia. Part D. Sc. thesis, University Western Australia, Dept. of Geology Library. – 1957: Some structural notes on charnockitic rocks. Mysore Geologists' Assoc., Bangalore, India Bull. 13.

THE PRECAMBRIAN OF NORTH-WESTERN QUEENSLAND, AUSTRALIA

by E. K. CARTER *)

With 2 Plates and 1 Figure

Abstract

Precambrian rocks, ranging in age from probable Archaean to Upper Proterozoic, crop out over an area of 25,000 square miles in north-western Queensland. They fall into four large divisions, separated by major unconformities. Little is known of the history of the Archaean rocks, which are believed to include altered acid lavas, schists, gneisses and migmatite. The Lower Proterozoic strata form part of an orogenic belt. The Lower Proterozoic lower sequence is rich in altered acid and basic lavas. It has a maximum thickness of not less than 40,000 feet and was strongly deformed by east-west pressure and probably intruded by granite before the Lower Proterozoic upper sequence was deposited. Sediments form the bulk of the Lower Proterozoic upper sequence; these accumulated most thickly to the west and north-west of the core of lower sequence belt, but overlie lower sequence strata. The greatest thickness of sediments is at least 40,000 feet. The sequence was deformed by a renewal of east-west compressive stresses, accompanied by granite emplacement. Folding is strong to moderate, but lacks well-defined linearity in the west of the outcrop area.

Upper Proterozoic sediments and lavas accumulated mainly in the west and north-west of the region. They are gently to moderately folded on west to north-west axes.

The Precambrian in north-western Queensland, excluding the Camooweal Dolomite, crops out over about 25,000 square miles. Systematic field work was started by joint teams of the Commonwealth Bureau of Mineral Resources and the Geological Survey of Queensland in 1950.

Reconnaissance mapping of the region was completed in 1954 but check work and more detailed mapping of areas of economic interest are still in progress. Maps are being prepared at a scale of 1 inch to 4 miles (1 : 253,440) and a report on the area is being written (CARTER and BROOKS, in preparation). The Camooweal Dolomite, of Upper Proterozoic or Lower Cambrian age, is not

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included. Its stratigraphic and palaeographic position is discussed by Noakes (1956).

The reconstruction of the geological history of the region presented below is an interpretation of the data obtained. The evidence is not sufficiently complete to enable a unique interpretation to be made of all aspects of the region's history. In particular the history of granite intrusion has not yet been completely unravelled.

Regional Setting

The Precambrian of north-western Queensland is part of the Shield area of Australia. It consists of a north-south belt of (?) Archaean and Lower Proterozoic rocks overlain, particularly in the north-west, by Upper Proterozoic strata which continue in a west-north-west-trending belt in the Northern Territory. The Upper Proterozoic rocks crop out in the Northern Territory continuously along the watershed south of the Gulf of Carpentaria and throughout much of Arnhem Land. Precambrian metamorphic and igneous rocks also occur in north-central Queensland, but the relationship between these and those of north-western Queensland is not known. Between them lies the Great Australian Artesian Basin, of largely unfolded Mesozoic strata (Whitehouse, 1954).

To the south of the Precambrian belt, rock outcrops are sparse, but Cambrian, Ordovician, and Mesozoic sediments have been mapped. Between the Lower Proterozoic belt and the Northern Territory border fossiliferous Middle Cambrian and younger sediments are underlain by the intracontinental (?) Camooweal Dolomite of Upper Proterozoic or Lower Cambrian age (Öpik, 1956 a, b; Noakes, 1956).

The Precambrian of the region is divided into four main parts (Plate 1):

1. The gently to moderately folded sediments and lavas of Upper Proterozoic age, which occur mainly in the west of the region. They have not been deformed by orogenies; they are folded on west to north-west axes, but display a strong tendency towards basin-and-dome structure; they are also practically unmetamorphosed and have only a small body of high-level granite associated with them.

2. The thick succession, of geosynclinal magnitude, of sediments and sparse lavas, which is described as the upper sequence of the Lower Proterozoic. These sediments are moderately to strongly folded on near-meridional axes, but in the west have numerous basins and domes; fracture-cleavage is developed in the less competent strata, but otherwise metamorphism is slight. Some granite crops out within the sequence; but many of the granite bodies which are exposed in the Lower Proterozoic lower sequence and the (?) Archaean strata may have been associated with the orogeny which deformed the upper sequence.

3. The lower sequence of the Lower Proterozoic which forms the eastern belt of the region is characterized by abundant lavas and is highly deformed, moderately to strongly metamorphosed, and extensively intruded by granite.

4. A north-south belt of highly altered igneous rocks occupies the core of an anticlinal structure. These rocks may represent the basement to the

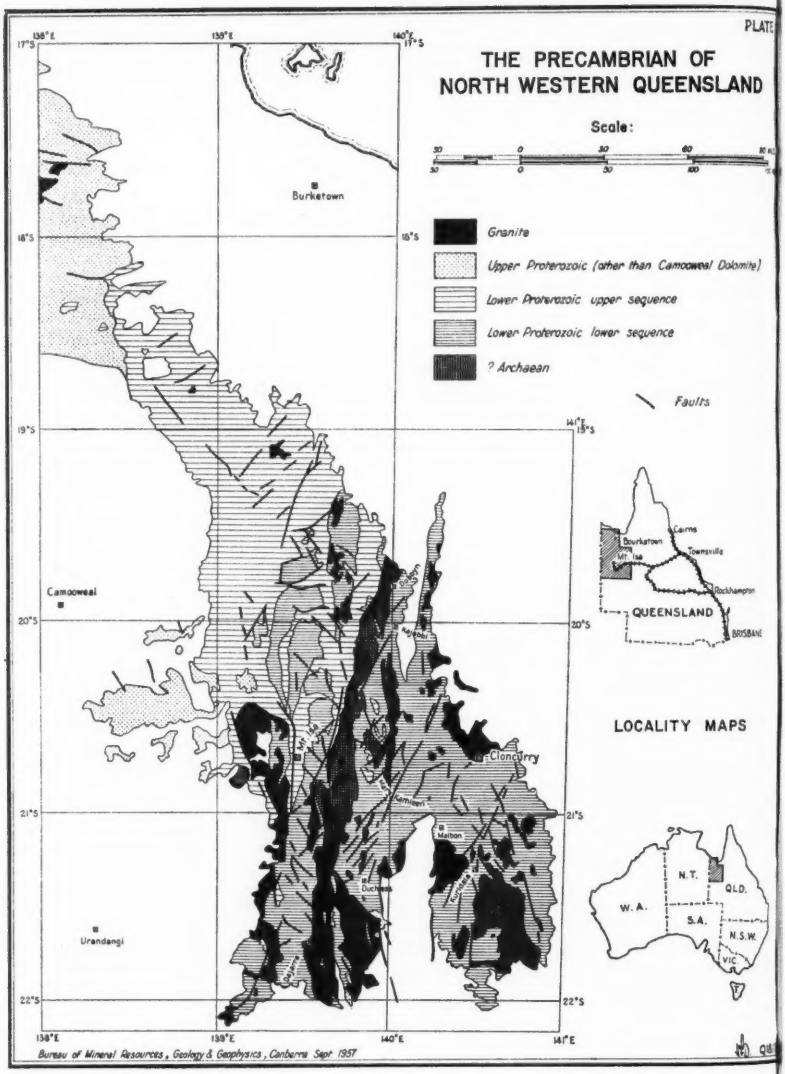


PLATE
THE PRECAMBRIAN OF
NORTH WESTERN QUEENSLAND
Scale:
Granite
Upper Proterozoic (other than Camooweal Dolomite)
Lower Proterozoic upper sequence
Lower Proterozoic lower sequence
? Archaean
Faults
Burketown
Camooweal
Urandangi
Cloncurry
Mt Isa
Townsville
Cairns
Rockhampton
QUEENSLAND
BRISBANE
LOCALITY MAPS
N.T.
QLD.
W.A.
S.A.
N.S.W.
VIC.
138°E
139°E
140°E
141°E
17°S
18°S
19°S
20°S
21°S
22°S
Bureau of Mineral Resources, Geology & Geophysics, Canberra Sept 1957

lower sequence strata, but relationships have not been adequately deciphered.

Ages of the Major Units

Two, and possibly three, orogenies have affected the region. As the time interval represented by the period of erosion which followed each orogeny cannot be determined, the ages of the various units cannot be established with certainty.

The strata described as Upper Proterozoic underlie the Lower Cambrian or Upper Proterozoic Camooweal Dolomite with a slight unconformity (Noakes, 1956, correlates them with the Adelaide System of South Australia). The length of time required for the formation of all the Upper Proterozoic units based on estimated rates of sedimentation may be of the order of 20—30 million years. *Collenia*-type fossils have been found in dolomite in the lower-middle part of the Upper Proterozoic succession.

The Lower Proterozoic upper sequence may be seen to underlie the Upper Proterozoic (but not the oldest strata) with a major angular unconformity. Allowing for a minimum period sufficient to produce the observed deformation and inferred erosion, the uppermost beds of the Lower Proterozoic upper sequence could be of Upper Proterozoic age. The evidence of extensive and well-developed colonies of algal fossils in the upper-middle part of the sequence may be interpreted as favouring an Upper Proterozoic rather than a Lower Proterozoic age for the sequence as a whole. However, the great thickness of the sequence (possibly in excess of 40,000 feet), could hardly have accumulated in less than 100 million years. The sequence is therefore considered to be for the most part of Lower Proterozoic age.

The lower sequence did not behave as a rigid block during the orogeny that folded the upper-sequence strata. Further, some probable algal fossils have been found in the calc-silicates of the Corella Formation. For these reasons the author prefers to regard the lower sequence as of Lower Proterozoic rather than Archaean age.

Any older rocks may reasonably be regarded as Archaean.

Archaean

Plate 1 shows a meridional belt of Archaean rocks more than 120 miles long and up to 20 miles wide east of the upper sequence. The rocks consist of recrystallized and metamorphosed acid lava, schist, gneiss, amphibolite, and migmatite.

The relationship between these rocks and overlying acid lavas has not been determined. No sharp structural or metamorphic break has as yet been found. At one point a conglomerate containing altered acid lava boulders was seen at the assumed contact. At another point a hornfelsed conglomerate, which contains boulders of granite and altered acid lava, has been recorded; but, owing to the complexity of structure, it has not been established whether the conglomerate occurs in a synclinorium, at the base of the Lower Proterozoic lower sequence, or in an anticlinorium.

Conglomerate and arkose generally mark the base, along its eastern margin, of an arenaceous succession which overlies the Lower Proterozoic acid lavas.

As the older acid lavas and metamorphics appear to be of a higher grade of metamorphism than the overlying acid lavas and metasediments and some of the field data can be interpreted as evidence for a structural break between the two, the older succession can be tentatively assigned to the Archaean and can be regarded as basement to the Lower Proterozoic rocks.

Petrological work has shown some of the rocks west and south-west of Mount Isa and north-west of Dajarra to be of anomalously high metamorphic grade (JOPLIN, 1955, also unpublished work by K. R. WALKER). However, no field evidence has been obtained to support the view that the rocks concerned are older than the oldest lower-sequence strata. They are therefore not mapped as Archaean. General tectonic considerations, however, require a foreland in the general position of these high-grade metamorphic rocks. Further mapping may reveal inliers of rocks of Archaean age.

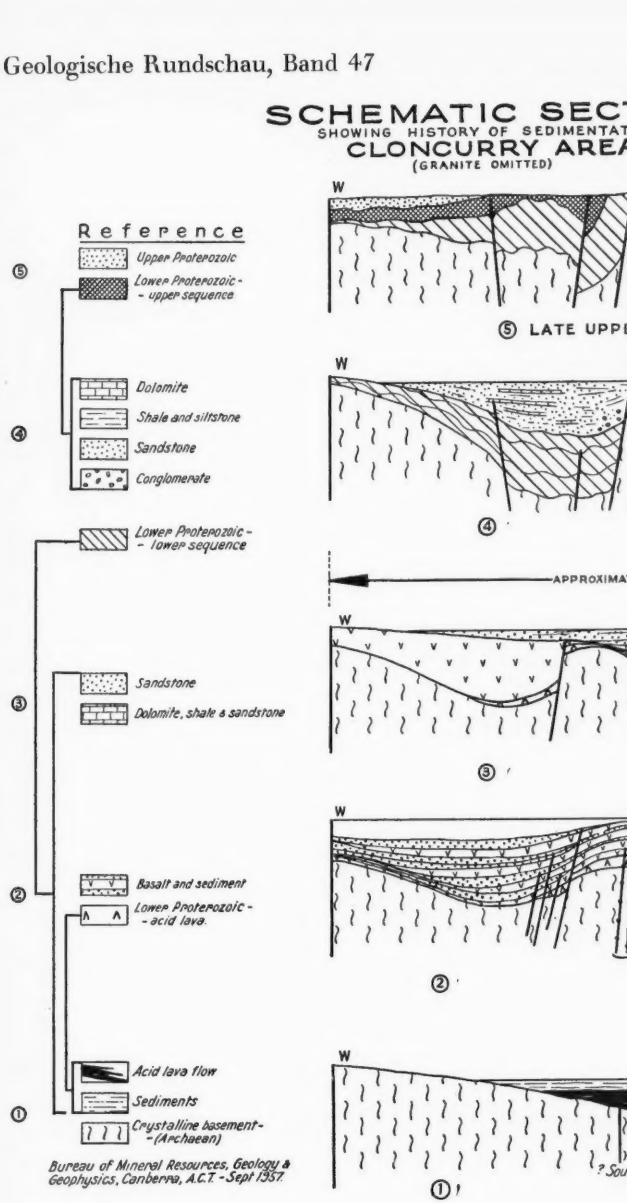
Some granites may also be of Archaean age. The Lower Proterozoic upper sequence has been observed to lie on a granite which intrudes the Archaean acid lavas. Although this granite is therefore older than the upper sequence, it is not known whether it is also older than the lower sequence. Pebbles and boulders of granite, presumably of Archaean age, form part of the conglomerate in the Lower Proterozoic acid lava succession.

Lower Proterozoic

Lower sequence

The history of the lower sequence in the centre of the outcrop area begins with acid vulcanicity. In the more westerly belt of the exposed acid lavas the flows were at first poured out on a land surface, but farther east (southwest of Cloncurry) the oldest known acid lavas (rhyolite) are interbedded with quartz arenites. The oldest exposed strata south-east of Cloncurry, probably of the same age as the acid lavas farther west, are devoid of acid lavas. The focus of acid vulcanicity was probably along, or just east of, the belt of Archaean rocks; the existence of vast sheets of porphyritic lavas, with few pyroclastics, appears to indicate fissure eruption. As the vulcanicity progressed the sea gradually advanced to the west to give interbedded lavas and sediments. The lavas also become more varied; tuff, agglomerate, and basalt overlie the main body of acid lavas, particularly in the west of the outcrop area. The westward extent of the lava-flows is not known.

The acid vulcanicity was succeeded by a period, with very little volcanic activity, in which a sheet of sandstone was spread over all, or nearly all, the region in a shelf environment. The sediment in the west derived its material from a nearby crystalline terrain, as is evidenced by its high feldspar content and by arkose and conglomerate at the base. This coarse



1 — Late stage of Lower Proterozoic acid
2 — Late stage of Lower Proterozoic basalti
3 — Close of Lower Proterozoic lower sequ
4 — Close of Lower Proterozoic upper sequ

SECTIONS
SEDIMENTATION
Y AREA
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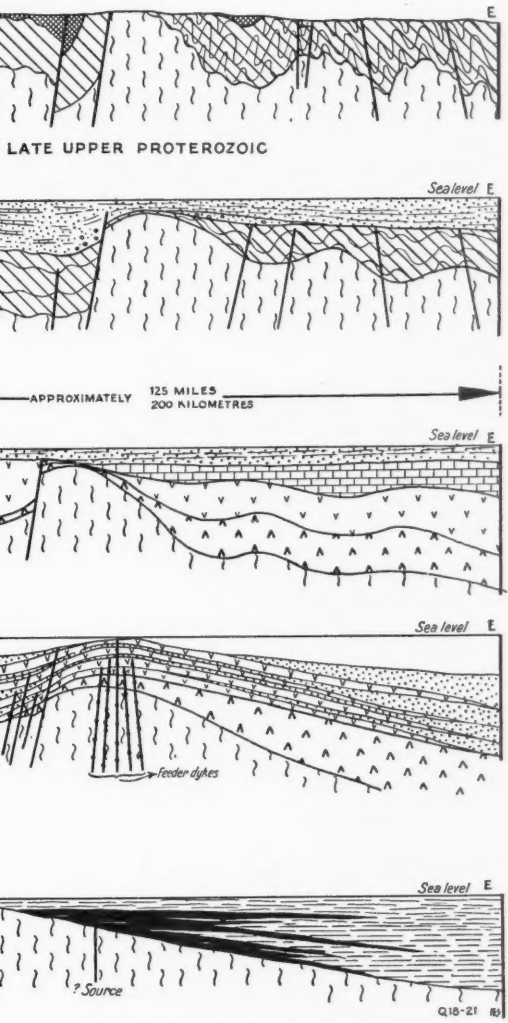

rozoic acid vulcanicity
ozoic basaltic extrusion
lower sequence sedimentation
upper sequence sedimentation

material may have come from the west or from a welt or tectonic land which may have begun to emerge at this early stage.

A prolonged period of basaltic extrusion ensued. The basic vulcanicity appears to have been centred along a meridional line about 20 miles east of Mount Isa, in roughly the same position as the acid vulcanicity. West of the outcropping Archaean metamorphics the basalt covered an area of at least 3,500 square miles and attained a thickness of not less than 10,000 feet. The basalt throughout is thinly interbedded with sediments except near the top of the succession, where quartzite lenses up to 2,000 feet thick occur. The metabasalts in two separate areas south-west and south-east of Cloncurry, are believed to be of the same age as the metabasalts farther west. From west to east the total volume and thickness of the metabasalt diminishes.

Considerable crustal movement was associated with the outpouring of the basalt. Subsidence of the western area in which the basalts accumulated was accompanied, and possibly produced, by meridional tensional faulting. In the course of time these lavas were let down against the Archaean acid lavas in some places. At some stage during the basic vulcanicity the welt or tectonic land, marked by the line of outcropping Archaean (though it may have been extended much farther east), began to emerge and was so eroded that by the time the succeeding sediments were deposited the basement was exposed. Throughout this anticlinal line extensive metadolerite and amphibolite dykes form an impressive swarm over a length of 200 miles. They are exposed only in formations older than, or contemporaneous with, the basaltic succession. They are therefore believed to be related, in part, to the period of basic vulcanicity and perhaps to have formed feeders to the flows.

By the time the vulcanicity began to wane the lower-sequence strata were accumulating in two clearly defined troughs. Their margins cannot now be precisely delineated; they may have been linked in places, but apparently open sea lay to the east of the eastern trough as there is no record of substantial sedimentation from that direction.

Crustal movement appears to have become more complex before the next younger major formation, a thick succession of pre-orogenic carbonate-rich sediments, was deposited. The single broad upwarp between the two troughs had been modified and two smaller, roughly meridional, probably submarine, ridges had formed to the east. Between these was a trough in which muds, silts and some carbonate rocks gradually accumulated. The warping of the sea-floor is further evidenced by an unconformity between the basaltic succesion south-east of Cloncurry and overlying calc-silicate rocks and by lines of calc-silicate breccia, apparently formed by slumping around margins of the submarine ridges.

The sea, and consequently the carbonate-rich sediments, gradually transgressed on to the main welt from the east, cutting across successively older formations as it advanced. The basalts had by this time been completely eroded from the welt. The sediments were thinly-bedded dolomite, shale and sandstone. A considerable thickness of sediments was probably depo-

sited over the now exposed metamorphosed dolomite and associated sediments, but only fragments, represented by quartzitic formations, are now left as evidence.

An orogenic phase, with lateral east-west compression, then folded the lower-sequence strata on approximately meridional axes and caused extensive shear-faulting. The orogenic deformation was probably accompanied and followed by extensive granite intrusion and moderate metamorphism, but direct evidence for granite emplacement at this stage has not been obtained. The difference in the grade of metamorphism between the upper and lower sequences, and the very widespread scapolitization of portions of the lower sequence (see EDWARDS and BAKER, 1954), lend support to the view that granite was emplaced before the upper sequence was laid down.

Upper sequence

The upper sequence is predominantly sedimentary; it started to form after uplift and a period of erosion of the lower sequence long enough to have produced a surface with strong topographic relief.

Near-meridional tensional faults formed the limits of the most deeply subsiding portion of the trough or basin. East-west cross-faults, which were confined to the block between the meridional faults, also increased the total subsidence, which resulted in a very deep structural basin north of Mount Isa. It probably shallowed greatly to the south; the northern extremity of the basin is concealed beneath soil and Mesozoic sediments.

In the early stages, at least, sediments were derived not only from the old foreland to the west and south-west, but also from the tectonic land to the east. Boulder conglomerates, with pebbles and boulders of acid lavas, basalt, quartzite, and quartz, mark the base of the upper sequence at its contact with the Archaean and the Lower Proterozoic lower sequence. At one point a basal arkose lies directly on granite associated with the Archaean basement.

The oldest strata of the upper sequence are generally fairly well bedded quartz arenites, ranging in grain size from medium and coarse sandstone to siltstone. The beds in the south and south-west apparently received their material from the low-lying foreland rather than from the tectonic land; they contain a greater proportion of silt and clay than those in the north and east.

A brief volcanic episode, in the course of which basic and acid lavas and agglomerate were extruded, was accompanied by some slight crustal movement. As a result boulder conglomerates and an unconformity developed locally. After the vulcanicity, sedimentation generally appears to have been less rapid than previously. Siltstone, shale, dolomite, dolomitic shale, and carbonaceous siltstone are together more abundant than sandstone.

Extensive exposures of biostromal algal remains have been found in the upper half of the Lower Proterozoic upper sequence. These display considerable variety in form. Some are of *Collenia*-type, but affinities have

not so far been studied. The line of outcrop lies a few miles west of the Mount Gordon Fault-zone, the westernmost of the near-meridional tensional faults referred to above.

The stratigraphic position of the shales which contain the large Mount Isa lead-zinc and copper orebodies has not been precisely fixed. They lie unconformably against the oldest formation in the Lower Proterozoic upper sequence. The sediments appear to have accumulated in a long, narrow trough between the old foreland and the tectonic land to the east, but may have extended over a much wider area. The shales are considered to form part of the Lower Proterozoic upper sequence.

It has also not been possible to establish whether or not a quartzitic succession which lies unconformably on the Lower Proterozoic lower sequence, between Cloncurry and Mount Isa, (and which is assumed, on structural, lithological, and metamorphic grounds, to be part of the upper sequence) originally formed a continuous sheet with the main body.

There appears to have been a slight recrudescence of vulcanicity in the youngest formation in the Lower Proterozoic upper sequence, in the extreme north-west of the sequence's area of exposure. Tuff and possibly rhyolite have been recorded.

The upper sequence, together with the lower sequence, was deformed by a renewal of east-west compression. Strong, generally north-pitching, folds developed in the eastern portion of the upper sequence; but farther west basin-and-dome structures are dominant. West of Mount Isa the structure displays the influence of an underlying rigid basement. A conjugate shear-fault system developed in the upper sequence; and further movement probably took place on the faults in the lower sequence. High-angle reverse-fault movement took place south of Cloncurry (Cloncurry overthrust) and west of Mount Isa (Mount Isa Fault). Movement on the Mount Isa Fault was considerable.

During orogenic deformation of the upper sequence the lower-sequence strata did not act as a rigid block but were further folded. Granite emplacement accompanied the orogenic deformation; only fairly small masses actually intrude the upper sequence, but probably some, and possibly all, the granites that crop out in the lower sequence were emplaced after the deposition of the upper sequence.

Uplift, succeeded by prolonged erosion, accompanied or followed the granitic intrusion.

Upper Proterozoic

Upper Proterozoic strata, other than the Camooweal Dolomite, are most extensively developed in the extreme north-west of the region, although sandstone crops out over a wide area west and north-west of Mount Isa. Small isolated bodies attributed to the Upper Proterozoic occur in several localities on or near the margin of the older strata. Of these, some may possibly be littoral equivalents of the Camooweal Dolomite. The age of several bodies of conglomerate, largely confined to small grabens in a north-trending belt which extends north-west of Cloncurry, cannot be

closely determined. They are unfossiliferous and are nowhere covered by younger rocks.

North of latitude 18° S, near, and extending into, the Northern Territory, are extensive lavas of Upper Proterozoic age. They have been subdivided into three stratigraphic formations. The lavas in the oldest formation are coarsely porphyritic, intermediate to acid, and were extruded on to a land surface. The magma from which the lavas were derived appears to have broken through the underlying strata and intruded the flows. The emplacement of the granite is believed to have predated the deposition of the younger formation — a conglomeratic succession.

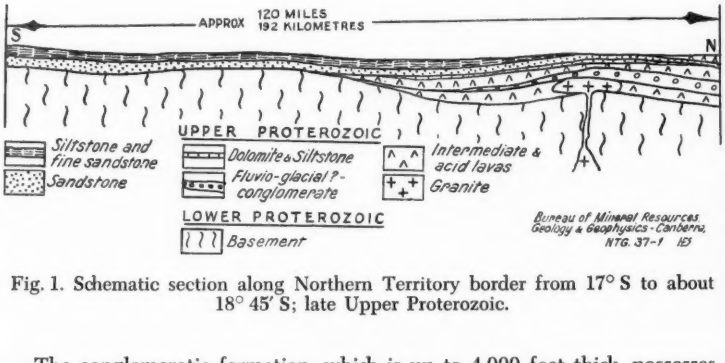

Fig. 1. Schematic section along Northern Territory border from 17° S to about 18° 45′ S; late Upper Proterozoic.

The conglomeratic formation, which is up to 4,000 feet thick, possesses some of the characteristics of a fluvio-glacial deposit and is derived from the east. It is overlain by the second volcanic succession, also of acid to intermediate lavas, but with some basalt, and with interbedded sediments. A dolomitic, arenaceous and argillaceous succession lies conformably above the second volcanic formation. *Collenia*-type fossils have been found in some of its dolomitic strata. The next two formations, the older of medium to coarse-grained sandstone and the younger of fine sandstone and siltstone, are best developed south of latitude 18° S, where two basins form the dominant structure. The medium to coarse grained sandstone formation lies with a major unconformity on Lower Proterozoic strata. The lavas and associated sediments that underlie this formation north of latitude 18° S are absent where the unconformity occurs. The dolomites, sandstones and siltstones all lense out to the north and north-west, in the Northern Territory. A third intermediate lava succession, which is believed to overlie the siltstone succession is well developed in the Territory.

Other sedimentary and volcanic formations, probably of Upper Proterozoic age, are known to overlie the strata described above, but relationships have not been fully deciphered.

The Upper Proterozoic arenaceous succession west of Mount Isa has been formed by erosion of the Lower Proterozoic strata to the east. It consists essentially of well-sorted medium-grained sandstone, with extensive

cross-bedding and ripple-marking. Some possibly deltaic deposits occur in the north-east of the outcrop area.

The Upper Proterozoic strata are generally moderately folded on east-west to north-west axes, but basin-and-dome structures predominate. Extensive tensional faulting has taken place; fault zones are commonly silicified but major quartz reefs are not formed. A further period of granite intrusion in the extreme north-west probably followed the high-level granite referred to above.

Despite the vulcanicity and granite intrusion north of latitude 18° S the sedimentation and deformation are characteristic of post-orogenic movements rather than orogenic tectonics.

Intrusive igneous rocks

The granites which intrude the Lower Proterozoic strata consist of two main petrological types (Joplin, 1955). The type most abundant in the west of the lower-sequence outcrop area is a coarse, porphyritic, generally foliated, biotite-microcline granite. Its composition and texture vary considerably from place to place, and it is commonly highly contaminated. In places hornblende is an important constituent. In the east of the region the second main granite type is preponderant. It is a fine-grained to medium-grained, fairly even-textured, massive microcline granite; ferromagnesian minerals are not as abundant as in the coarser granite. Wherever the mutual relationships have been established the fine-grained intrudes the coarser granite.

Although the granites can be divided into two broad types, each type is very variable. The variation probably reflects in part such factors as degree of contamination, hybridization, and granitization, local stress environment, and abundance of associated fluids. However, as granite may have been emplaced at three different times, the variations may occur largely between granites of different ages. Dr. Joplin has recently suggested (personal communication) that pairs of coarse-grained foliated (syn-orogenic) and fine-grained, massive (post-orogenic) granites may be associated with each orogeny.

A muscovite-rich granite intrudes the upper sequence sediments 90—120 miles north-north-west of Mount Isa, but only fairly small bodies crop out.

Pegmatities are locally, but not generally, abundant. In the central portion of the lower sequence the pegmatites tend to be rich in microcline or albite, but around the periphery of the lower-sequence outcrop area they are muscovite-rich.

Soda aplites and albitite are also widespread. They form numerous small bodies which cut the two main granite types. The age relationship of the pegmatites to the albitite has not been established.

The Upper Proterozoic granite in the extreme north-west of the region is considered to be younger than those discussed above; it also probably has intrusions of two ages. The older is red, porphyritic and coarse-grained and has the composition of adamellite. It is poor in quartz and in ferro-

magnesian minerals. The younger granite is a biotite granite with crystals of white feldspar.

Throughout the whole region field evidence of intrusion and of unconformity with exposed granite shows that granitic intrusion took place —

1. Prior to the deposition of the Lower Proterozoic upper sequence.
2. After deposition of the upper sequence (at least two granite types).
3. After the extrusion of the oldest Upper Proterozoic lava succession and before the deposition of the next younger (conglomeratic) succession.
4. Probably intruding younger Upper Proterozoic strata (present evidence inconclusive).

Granite pebbles in the Lower Proterozoic lower sequence prove the existence of granite of (?) Archaean age in the region.

Petrological work on grades of metamorphism (largely unpublished) by Walker and Joplin demonstrates that granite probably intruded the Lower Proterozoic lower sequence before the upper sequence was laid down.

At least four phases of doloritic and gabbroic injection can be recognised, but the history is probably even more involved. In the Archaean metamorphics two ages of basic rock are widespread. The older, now generally amphibolite or part of a migmatic suite, may form part of the Archaean complex. The younger is generally metadolerite or amphibolite and is thought, on grounds already given, to be related to the Lower Proterozoic lower sequence basic vulcanicity. Widely distributed throughout the Lower Proterozoic lower sequence are dolerites, microgabbro, and gabbro, which generally occupy structural positions in the noses of folds or faults; many of them have been affected by granite. Some dolerites occur in the upper sequence; but whether most of this group of basic intrusives is older or younger than the upper sequence sediments is not yet established. Unaltered post-granite dolerites, which generally strike east-west, are widespread, though sparse, throughout the lower sequence. Dolerites, probably of the same age, also appear in the Mount Isa Shale. Dolerite has been recorded in the Upper Proterozoic strata in the extreme north-west of the region; it is probably related to the basic lavas of the area.

Joplin (1955) has briefly described the basic rocks of the district. The scarcity of olivine in the basic intrusives and lavas and the absence of ultrabasics is noteworthy.

Conclusions

The Lower Proterozoic of North-western Queensland formed an orogenic belt, although not as big nor as complex as later belts throughout the world, nor possessing many of their typical features. Despite the unusually large proportion of lavas in the Lower Proterozoic lower sequence, crustal instability was not sufficient to produce an abundance of the typical greywackes of many later orogenic belts.

The full length of the belt is not exposed, but it is believed that almost the whole original width (after deformation) can be seen. The belt did not

undergo severe lateral compressive stresses; crustal shortening was fairly small. As a result Alpine type structures did not develop (Alpine structures, however, are absent from orogenic belts, of whatever age, on the Australian continent).

Structurally the belt, particularly the lower sequence, is remarkably symmetrical although there is no evidence that appreciable quantities of sediments were derived from east of the belt. There is, however, some evidence that a crystalline block of granitic composition lay to the east.

The development of the Lower Proterozoic orogenic belt was probably one of the final major steps in the welding together of nuclei to form the Australian Precambrian Shield. The Upper Proterozoic vulcanicity and tectonics may reflect the action of orogenic processes elsewhere or may have been due to a minor consolidation process. In Palaeozoic times several depositional basins formed within the Shield area of north-western Queensland, but probably at no time since the deformation and uplift of the upper sequence strata has the whole of the Precambrian of north-western Queensland been submerged beneath the sea.

Mapping during 1957 has shown that the unconformity between the Lower Proterozoic upper and lower sequences is present only along the western margin of, and east of, the tectonic land. Further west the passage from the basaltic succession of the lower sequence to the lowermost arenaceous succession of the upper sequence is conformable.

The interpretation of the tectonic history given above is modified as follows: The calc-silicate and overlying formations of the lower sequence east of the tectonic land are regarded as contemporaneous with the basal arenaceous succession of the upper sequence west of the tectonic land.

The first Lower Proterozoic orogenic compressive phase, which deformed the lower sequence strata and interrupted sedimentation (and probably had intrusive igneous activity and metamorphism associated with it) east of the tectonic land, produced only minor deformation, with local unconformity, west of the tectonic land. Sedimentation west of the tectonic land generally was continuous at this time; the lavas may be genetically related to the syn-orogenic igneous activity farther east.

References

Carter, E. K., and Brooks, J. H. (in preparation): The Precambrian Mineral Belt of North-western Queensland. Bur. Miner. Resour. Aust. Bull. **51.** — Edwards, A. B., and Baker, G., 1954: Scapolitisation in the Cloncurry district of North-western Queensland. J. geol. Soc. Aust., **1,** 1—33. — Holmes, A., and Smales, A. A., 1948: Monazite from Bodmin Moor, Cornwall: A study in geochronology. Proc. Roy. Soc. Edinb., Sec. B, **63** (2), 115—129. — Joplin, G. A., 1955: A preliminary account of the petrology of the Cloncurry mineral field. Proc. Roy. Soc. Qld., **66** (4), 33—67. — Nier, A. A., Thompson, R. W., and Murphey, B. F., 1941: The isotopic composition of lead and the measurement of geological time. III. Phys. Rev., **60,** 112—116. — Noakes, L. C., 1956: Upper Proterozoic and Sub-Cambrian rocks in Australia. In: El sistema cambrico, su paleogeografia y el problema de su base. **2,** 213—238. 20th Int. geol. Congr., Mexico. — Öpik,

A. A., 1956 a: Cambrian geology of Queensland. Ibid., **2**, 1—24. — ÖPIK, A. A., 1956 b: Cambrian palaeogeography of Australia. Ibid., **2**, 239—284. — WHITEHOUSE, F. W., 1954: Geology of the Queensland portion of the Great Artesian Basin. Appendix G of Artesian water supplies in Queensland. Dep. of Co-ordinator of Public Works, Queensland.

THE OLDEST FOSSIL FAUNAS OF SOUTH AUSTRALIA

by M. F. GLAESSNER, *University of Adelaide*

With 5 figures

Abstract

A critical review of earlier references to Precambrian fossils in South Australia shows that Radiolaria could be present but that other animal remains listed or described by earlier authors have been wrongly interpreted. There is no evidence for the presence of Arthropods in this material.

The fauna described by SPRIGG from the "early Cambrian" sandstone and quartzite of Ediacara consists not only of "Medusae". Recent studies have shown that it includes specimens resembling the types of *Pteridinium* and *Rangea* from the Nama Series of Southwest Africa. They are now considered as related to living Pennatulacea. In addition, there are present the annelid *Spriggina*, possibly Siphonophora, and at least two entirely new forms of invertebrates.

This assemblage is followed by a sequence of undoubted Lower Cambrian faunas from the lowest Archaeocyatha horizon up to the *Protolenus*-Zone. The Ediacara fauna which consists only of soft-bodied animals is entirely unlike any known Cambrian fauna. This fact supports the view that it is Precambrian.

Introduction

The search for the earliest signs of life in the history of the earth is as old as the study of ancient rocks. In South Australia it started almost as soon as the presence of a thick sequence of unmetamorphosed Precambrian and Cambrian rocks was established. This search owed much to the unfailing enthusiasm of HOWCHIN and DAVID whose findings were widely publicised and attracted much attention. Recent advances in the absolute dating of early rocks together with the progress of theoretical and experimental biochemical study of the origin of life have stimulated interest in the oldest fossils, and palaeontological data are under review in all continents. If the observations made in South Australia in the first thirty years of this century are now critically reviewed, it is not done with the intention of detracting from the esteem with which we generally contemplate the unlimited energy and enthusiasm of the pioneers. Rather, it is necessary to take account of changing viewpoints and methods, new discoveries which have been made and questions which have been asked, to prevent a distorted picture from being perpetuated in the world literature. One may also hope that today's stocktaking may help to renew the enthu-

siasm of the early days of exploration and that the present limits of our knowledge will be seen as a challenge.

WHITTARD (1953) and SCHINDEWOLF (1956) have recently reviewed the problem of the oldest fossils. They have discussed fossil plants as well as animals. It is now well known that fossil algae represented by stromatoliths, occur through a considerable part of Precambrian time. The organic origin of such fossils as *Collenia* has rarely been disputed though SCHINDEWOLF (1956, p. 463) links them with ooliths as pseudofossils and finds it strange ("sehr auffallend") that no organic structures are preserved. This, however, is the nature of the stromatoliths which are formed by lime-precipitating but not by lime-secreting algae. They are known from the Precambrian of South Australia but as their taxonomy and evolutionary changes in the course of time must remain problematic, they will not be discussed here. The discussion of the oldest fossil animals will be based on the available material and data and will not include detailed references to statements on taxonomy or stratigraphic position of South Australian fossils by the authors of various recent reviews published in other countries.

Supposed Precambrian animal remains

The latest summary of the Geology of Australia (DAVID, 1950) includes the following references to Precambrian fossils from South Australia:

1. Radiolaria (Crystal Brook).
2. Sponge spicules (Montacute).
3. "*Protadelaidea*" (Teatree Gully).
4. "Giant annelids and arthropods", pteropods, phyllocarids, minute brachiopods, *Beaumontia* (Beaumont Dolomite of Adelaide).
5. "Dwarfed annelids and arthropods" (Brighton Limestone).
6. Radiolaria (Brighton Limestone).

The localities of these supposed fossils are here arranged in ascending stratigraphic order to represent various horizons of the lower and middle part of the Adelaide System (Torrensian and Sturtian Series, MAWSON and SPRIGG, 1950). All are now known to be well below the fossiliferous Lower Cambrian though some of them, particularly the Brighton Limestone, had been placed in the Cambrian by earlier authors.

These Precambrian "fossils" will be discussed in the order in which they appear in this list.

1. The supposed radiolaria from Crystal Brook were first described by DAVID and HOWCHIN (1896, p. 576, pl. 39, figs. 1—3) as follows "... In the black chert of Crystal Brook, the radiolarian casts are chiefly in the form of small spherical or oval nuclei of chalcedony, with a more or less distinct partially translucent outer ring of chalcedony. Much black opaque matter is present in this rock, as well as small spherical developments of iron pyrites, very suggestive of being inner casts of radiolaria. Their diameter varies from .1 mm. to .2 mm. Figs. 1—3 are very suggestive of forms allied to *Carposphaera*."

A slide in the collection of the Geology Department of the University of Sydney of a dark chert from Crystal Brook, South Australia, is labelled "Good radiolaria" and bears a red marker. It can be taken as a type slide though individual figured forms are neither marked nor recognizable. The section contains numerous translucent subcircular areas, with diameters mostly around 0.1 mm. None shows the dark rim around the light centre figured by DAVID and HOWCHIN. Dr. B. SKINNER who kindly examined the slide mineralogically, found that the spheres consist of mixtures of quartz and calcite without sharp boundaries against the ground mass, and that they grade into veins crossing the section and consisting of identical material. They are therefore secondary segregations, not of organic origin. A larger specimen (p. 527, fig. 5) resembles DAVID and HOWCHIN's fig. 2 and shows a dark centre. The slide is too thick for its finer structure to be clearly resolved. This may be an organic structure. The dark probably carbonaceous material in the cherts could contain other organic skeletal structures. Studies of insoluble residues of these cherts are now in progress but as yet no distinctive structures have been found.

2. The sponge spicules from Montacute are said to be 1.4 mm. long (DAVID, 1950, p. 78). This report appears to be based on a specimen figured by DAVID (1928, pl. 18, f. 6). This was described as "an unknown organism" on p. 202 but as "a laminar body, apparently spicular, possibly a sponge ..." on p. 209. The "spicules" have not been figured.

3. *Protadelaidea howchini* TILLYARD was described together with *P. browni* TILLYARD in great detail (in: DAVID and TILLYARD, 1936, pp. 64—84, pls. 1—10). This author's interpretative descriptions have not been accepted as proof of his far-reaching conclusions (see TEICHERT, in HUPÉ, 1952, p. 314). The prevailing view is that these impressions in quartzite represent mud flakes or flattened clay pellets (HUPÉ, 1952). In the writer's personal opinion they could have been formed also by pyritized soft plant tissue. This could account for the iron-staining of these areas in the weathered outcropping rocks. The only support for this interpretations as organic remains lies in the rather regularly angular outlines — a weak argument indeed. The evidence for their organic nature given by DAVID and TILLYARD, pp. 12—18, under 6 points is unconvincing. These points are: bilateral symmetry (1), segmentation (2, 3), sculpture (4), duplication of parts (5), coordination and balance of parts (6). Most of these points as formulated pre-suppose an animal and particularly an arthropod as originator. Nothing but vaguely regular outlines are known; the substance, original surface structure and connections of the moulded bodies remain unknown. Even if produced not by mud flakes but by the thallus of a plant, these impressions tell us nothing about it.

4. The described remains from the Beaumont Dolomite (formerly known as "Blue Metal Limestone") are even less impressive. A number of them were named *Beaumontia eckersleyi* DAVID (1928, p. 203, pl. 18, fig. 1). A specimen on pl. 17, fig. 7, is described as "*Beaumontella eckersleyi*" on p. 208 where "fig. 1" is designated as the type. The context makes it clear that this refers to pl. 18, fig. 1, a vaguely claw-like nodular body.

In an addendum published in the following year David refers consistently to "*Beaumontella*". These nodular shapes were interpreted as various parts of Eurypterids. The reports of "giant annelids and arthropods", "pteropods", and "phyllocarids" from the same formation are based on similar specimens (David, 1928, p. 202; "Annelids appear to be present . . ."). The "minute brachiopods" were described by Chapman (1929, p. 5) but structural evidence supporting their identification as organic remains is lacking. Their size is 3 to 5 mm.

5. "Annelids" and "arthropods" from the Brighton Limestone of Brighton and Reynella were described by David (1922, 1928). One specimen was named *Reynella howchini* (p. 199 f., pl. 16, fig. 1—3). There is no specific reason for considering these exceedingly irregular shapes as organic. The only micro-photograph presented from this locality (pl. 15, Fig. 1) bears the legend "Fig. 1 is a photograph (by H. G. Gooch) of a problematical body, possibly allied to *Stratiodrilus*. It has been suggested that it is not necessarily organic at all, but is formed by the junction of two or more crinkled laminae of inorganic origin."

The study of slides in the collections of the Geology Departments of Sydney and Adelaide Universities supports this interpretation. One of the slides is marked "spiral algae" but the dark zig-zag laminae to which this seems to refer show no organic structure. I am informed by Dr. B. Skinner that irregular structures including spirals are not uncommon inorganic segregations in cherts.

The small ochreous impressions described as Crustacea (David, 1922) are quite indefinite and do not suggest Crustacean affinities.

6. A slide in the collection of the Geology Department of Adelaide University containing a specimen from the Brighton Limestone identified by Howchin as a radiolarian was examined by Mr. W. Riedel. This well-known specialist found no convincing evidence for this identification. The specimens figured by David and Howchin (1896, pl. 39, figs. 4—8) have not been found. It is possible that they are in fact radiolaria but little more than their size and siliceous composition supports this identification.

The result of this review is that the occurrence of Radiolaria and possibly other "Protista" in the Torrensian and Sturtian Series of the Adelaide System remains a possibility but that there is at present no new or more precise evidence than that presented by David and Howchin sixty years ago. All other claims are entirely unsubstantiated and in particular there is no evidence whatever for the postulated existence of arthropods. The proposed "generic" names *Reynella, Beaumontia* (= *Beaumontella*) and *Protadelaidea* are not based on recognizable animal remains.

A fauna from near the base of the Cambrian

Sprigg (1947, 1949) described the first "early Cambrian" fossils from the Pound Sandstone of Ediacara, about 300 miles north of Adelaide. The fossils occur in one or two thin bands extending some three miles along the strike of this quartzite formation where it forms the western limit of a syncline. The quartzite may be 2000 feet thick in this area (Daily, 1956,

p. 118). The fossils are found approximately 100 feet below its top which is conformably overlain by the Archaeocyatha-bearing Ajax Limestone. The first Archaeocyatha occur in it at this locality about 500 feet above its base (SPRIGG, 1947, p. 213). The latest classification of the fossils described by SPRIGG was given by H. J. HARRINGTON and R. C. MOORE in Part F (Coelenterata) of the Treatise on Invertebrate Palaeontology in 1956. It can be tabulated as follows:

Class Dipleurozoa
  Order Dickinsoniida
    Fam. Dickinsoniidae: *Dickinsonia costata* SPRIGG and other species

Class Scyphozoa
  Subclass Scyphomedusae
    Pseudorhopilema chapmani SPRIGG, 1949
    Pseudorhizostomites howchini SPRIGG, 1949

Class Hydrozoa
  Order Trachylinida
    inc. sedis: *Ediacaria flindersi* SPRIGG, 1947
      (including *Tateana* SPRIGG and *Cyclomedusa* SPRIGG)
  Suborder Trachymedusina
    Fam. Trachynematidae
    ? *Beltanella gilesi* SPRIGG, 1947
  Order Hydroida
    Suborder Calyptoblastina (= Leptomedusae)
      ? *Protodipleurosoma wardi* SPRIGG, 1949

Other genera and species are classified by HARRINGTON and MOORE as "Medusae incertae sedis". This classification will be reviewed in due course but the suggestion is made now that *Dickinsonia* (p. 527, fig. 4) is not a Coelenterate but an Annelid, possibly related to the living genus *Spinther* (Order Amphinomorpha) or to the ancestors of the living parasitic Myzostomids.

In December 1956 and September 1957 much further material was found at the Ediacara locality by two private collectors, Mr. H. MINCHAM and Mr. B. FLOUNDERS, and generously presented by them to the South Australian Museum. Further collecting has been carried out by joint field parties from the South Australian Museum and the University of Adelaide, and by other parties under the direction of Mr. SPRIGG. The large amount of material will require prolonged detailed study. In addition to large numbers of Medusae and *Dickinsonia* it includes specimens closely resembling *Pteridinium simplex* GÜRICH (particularly the neotype figured by RICHTER, 1955, pl. 1, but not so much the other specimens figured by him) and *Rangea schneiderhöhni* GÜRICH (l. c. pl. 7, fig. 12) from the Kuibis quartzite of the Nama Series of Southwest Africa. It is of interest that the Nama Series which from field evidence is placed in the Late Precambrian or Early Palaeozoic, also contains a Medusa and a cast described as having archaeocyathid or sponge-like characters. RICHTER had assigned *Pteridinium* and *Rangea* to the Gorgonacea but I consider *Rangea*

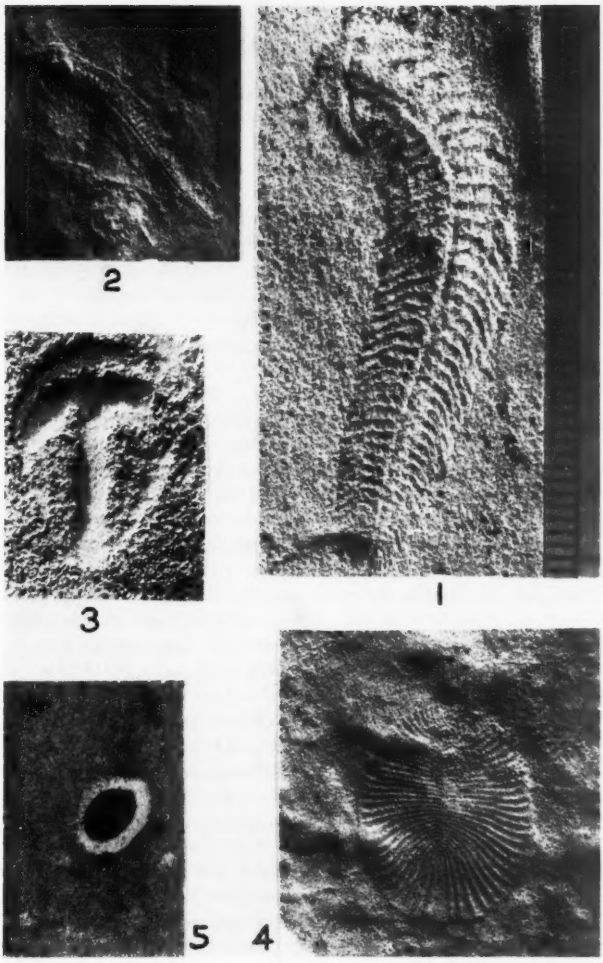

Fig. 1—4. Fossils from quartzite near the base of the Lower Cambrian, Ediacara, South Australia.

Fig. 1 and 2. *Spriggina floundersi* GLAESSNER. Fig. 1 — × 2, Fig. 2 — Nat. Size. Photos M. J. WADE.

Fig. 3. *Parvancorina minchami* GLAESSNER. × 5, Photo M. J. WADE.

Fig. 4. *Dickinsonia minima* SPRIGG. × 1.2, Photo K. PHILLIPS.

Fig. 5. Thin section of chert from the Lower Adelaide System (Proterozoic), Crystal Brook, South Australia, showing spheroidal meshwork of graphite surrounded by silica shell in dark ground mass, (Univ. Sydney Geol. Dept. coll.). × 56, Photo M. J. WADE.

Photos 1—3 are of impressions (external moulds) but may appear as if representing raised bodies, as a result of lighting arranged for greatest clarity of structure.

as a Pennatulacean comparing it with *Pteroeides*, and see in *Pteridinium* a closely related form. These relationships which are of very great interest from the viewpoint of evolution as well as of stratigraphy will be discussed elsewhere when the material is described. The abundant new collections include also a few specimens which may be interpreted as Siphonophora, and at least two entirely new forms of soft-bodied animals, each of them represented by numerous specimens. One is still undescribed; I have described and figured (GLAESSNER, 1958) the first-found specimen of the other as *Parvancorina minchami* (pl. 1, fig. 3), together with the remarkable *Spriggina floundersi* (p. 527, figs. 1, 2) which I have placed in a new family Sprigginidae of the Annelida, Class Polychaeta. Annelid affinities are shown by the unsegmented horseshoe-shaped head which is followed by up to about 40 undifferentiated segments tapering at the posterior end. Each segment bears a pair of appendages which are apparently unsegmented parapodia ending in long thin acicular setae. These are directed outward and backward. An impression of the pharynx can be seen behind the head in all specimens. The two larger specimens are 46 and 40 mm. long with a maximum width of 11 and 10 mm. An immature specimen with about 20 segments is 15.5 mm. long and 5.5 mm. wide.

The only similar living Annelids (no similar fossils are known) belong to the family Tomopteridae which is pelagic and has paddle-shaped terminations of the parapodia. The head projects laterally as a pair of tentacle-like extensions followed by a pair of very large tentacular cirri each containing a strong acicular seta. It is interesting to note that at least one of the specimens shows what appear to be acicular setae extending from behind the head projections along the sides of the body. In the Tomopteridae these structures are considered as derived from post-cephalic parapodia which were incorporated in the head. If this is the origin of the horseshoe-shaped head of *Spriggina*, it would indicate, firstly, that the Tomopteridae are represented at the beginning of Cambrian time by the Sprigginidae which resemble them but lack the specialisation of the parapodial terminations and the excessive development of the tentacular cirri. Secondly, these early primitive Annelids could throw some light on the problem of the ancestors of the Arthropods. The horseshoe-shaped head of *Spriggina* could well be the predecessor of the acron of the trilobites; it resembles the frontal portion of the early trilobite larvae. The fourpronged headshield of the Middle Cambrian genus *Marella* resembles the two pairs of cephalic appendages of *Tomopteris* more than any known arthropod head. These morphological relationships will have to be carefully re-examined on the basis of a more detailed investigation of the morphology of the first well-preserved Annelid from near the base of the Cambrian. The presence of numerous undoubted jellyfish proves that soft-bodied animals could be preserved in this quartzite, and that at this locality numerous pelagic organisms became rapidly embedded in sediment. In these circumstances we can expect most important contributions to our knowledge of the life of the open sea at the dawn of the

Palaeozoic Era when the change from soft-bodied to shell-bearing animals, and possibly also from open-sea to littoral habitat occurred. The earliest Metazoa in South Australia are Coelenterates and Annelids. These were apparently primitive but there are indications of a relationship to the ancestors of the Arthropods.

The earliest definitely Cambrian fossils

The Cambrian in South Australia was reviewed recently by Daily (1956). He recognized a number of different faunal assemblages consisting of Archaeocyatha, trilobites, brachiopods, sponges, and *Hyolithes*. Most of these have yet to be described and differ from those of other continents. The Archaeocyatha were the subject of Taylor's outstanding monographic work nearly 50 years ago (1910) and of much work by R. and J. and R. and W. R. Bedford (1934—1939). The stratigraphic evaluation of these species has not yet been attempted. The Archaeocyatha appear before the first trilobites, as they do in Morocco (Hupé, 1952) and Western Siberia (Lermontova, 1951). They are accompanied by sponge spicules and rare unidentified brachiopods (Daily's Assemblages 1 and 2). Next comes "Assemblage 3", the first known trilobite assemblage with *Yorkella*, accompanied by *Hyolithes* and the gastropods *Helcionella* (recte *Pseudotheca* according to Schindewolf, 1955) and *Pelagiella*. Some of the South Australian trilobites which differ generically from those of other continents have been wrongly placed in various European and North American genera including *Protolenus*. Their Lower Cambrian age, however, is fixed beyond doubt by the occurrence on Kangaroo Island of a fauna with the Protolenid *Lusatiops* n. s p. and with a *Redlichia*, of Late Lower Cambrian age, above boulder conglomerates containing boulders of Archaeocyatha limestone and therefore younger than Assemblages 1—2. It is known from recent stratigraphic observations by B. Daily that the conglomerates follow above the Parara Limestone in the type area where the limestone contains Assemblages 3 and 4.

The upper age limit of the first four Cambrian faunas is thus fixed as early Lower Cambrian by the occurrence in younger strata of a late Lower Cambrian fauna representing the widespread *Protolenus*-Zone. There is also a Middle Cambrian fauna (Daily's "Assemblage 10") well above the various Lower Cambrian assemblages.

Stratigraphic considerations

The lower limit of the Cambrian is as problematic in this area as it is elsewhere where sedimentation continued uninterrupted from definite Precambrian to definite Cambrian. Nevertheless, geological studies by Sir Douglas Mawson and by the South Australian Department of Mines, and Daily's recent work (1956) have clarified the facts to such an extent that the problem is now confined to an interval which is much narrower than recent statements in the literature on the oldest fossils would suggest.

I have recently (Glaessner, 1955) discussed the time-stratigraphy of the Precambrian and its nomenclature. The term Late Proterozoic for the

80 Million years preceding the beginning of the Cambrian (dated at about 520 M. yrs.) seems more appropriate than Eo- or Infracambrian or Late Algonkian though possibly Riphaean (or Rifean) is a better term still. Recent datings of pre-Sturtian uraniferous granites in South Australia shows that the middle portion of the Adelaide System is well within the Late Proterozoic. The Sturtian contains the clearest record of its glacial phase. It is preceded by the Torrensian which is also thought to be Late Proterozoic. The Brighton Limestone is accepted as the top of the Sturtian. As another series, the Marinoan, lies between it and the lowest Cambrian Archaeocyatha limestones, the earlier view that it may be basal Cambrian which is often quoted from older literature, is contrary to stratigraphic facts. The problem of the Precambrian-Cambrian boundary has been narrowed down to the question whether it is above or below the Pound Quartzite which it is the top unit of the Marinoan — and for the present it can be left there, until we develop more refined methods of absolute dating and of biostratigraphic correlation between faunal provinces. The fact, however, that the rich assemblage of fossils from the Pound Quartzite is entirely unlike any known Cambrian fauna supports the view that it is Precambrian.

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References

Bedford, R., and J., 1936: Further notes on Cyathospongia (Archaeocyathi) and other organisms. Mem. Kyancutta Mus. S. Aust., no. 3, pp. 21—26. – 1937: Further notes on Archaeos (Pleospongia). Mem. Kyancutta Mus. S. Aust., no. 4, pp. 27—38. – 1939: Development and Classification of Archaeos (Pleospongia). Mem. Kyancutta Mus. S. Aust., no. 6, pp. 67—82. — Bedford, R., and W. R., 1934: New species of Archaeocyathinae and other organisms from the Lower Cambrian of Beltana, South Australia. Mem. Kyancutta Mus. S. Aust., no. 1, pp. 1—7. – 1936: Further note on Archaeocyatha (Cyathospongia) and other organisms. Mem. Kyancutta Mus. S. Aust., no. 2, pp. 9—20. — Chapman, F., 1929: Some fossil remains from the Adelaide Series of South Australia. Trans. Roy. Soc. S. Aust., vol. 53, pp. 5—6. — Daily, B., 1956: The Cambrian in South Australia. XX Cong. Geol. Intern. Mexico, El Sistemo Cambrico, etc. Sympos., Pt. II, pp. 91—147. — David, T. W. E., 1922: Occurrence of remains of small Crustacea in the Proterozoic (?) or Lower Cambrian (?) rocks of Reynella near Adelaide. Trans. Roy. Soc. S. Aust., vol. 46, pp 6—8. – 1928: Notes on newly-discovered fossils in the Adelaide Series (Lipalian?) South Australia. Trans. Roy. Soc. S. Aust., vol. 52, pp. 191—209. – ed. Browne, W. R., 1950: The Geology of the Commonwealth of Australia. London. – and Howchin, W., 1896: Note on the occurrence of casts of Radiolaria in Pre-Cambrian (?) rocks, S. Aust. Proc. Linn. Soc. N.S.W., vol. 21 (4), pp. 571—583. – and Tillyard, R. J., 1936: Memoir on fossils of the later pre-Cambrian (Newer Proterozoic) from the Adelaide Series, S. Aust. Sydney. — Glaessner, M. F., 1955: Time-Stratigraphy of the Late Pre-Cambrian. Proc. Pan Ind. Ocean Sci. Cong., Perth, W. Aust. –

1958: New fossils from the base of the Cambrian in South Australia. Trans. Roy. Soc. S. Aust. vol. 81, pp. 185—188, pl. 1. — Hupé, Pierre, 1952: Contribution a l'Étude du Cambrien inférieur et du Précambrian III de l'Anti-atlas Marocain. Service Géol. du Maroc. Notes et Mém. 103. — Lermontova, E. V., 1951: Lower Cambrian Trilobites and Brachiopods of Eastern Siberia. Moscow, Gosgeolisdat. (F i d e : L. L. Khalfin, Atlas index fossils W. Siberia. Moscow 1955.) — Mawson, D., and Sprigg, R. C., 1950: Subdivision of the Adelaide System. Aust. J. Sci., vol. 13, no. 3, pp. 69—72. — Schindewolf, O. H., 1955: Die Körperfossilien des Unterkambriums. in: O. H. Schindewolf and A. Seilacher, Beiträge zur Kenntnis des Kambriums in der Salt Range (Pakistan). Akad. Wiss. Lit. Mainz. Abh. (1955), no. 10, pp. 25—85. – 1956: Über präkambrische Fossilien. Geotekt. Symp. H. Stille, ed. F. Lotze, Stuttgart, pp. 455—480. — Sprigg, R. C., 1947: Early Cambrian (?) Jellyfishes from the Flinders Ranges, South Australia. Trans. Roy. Soc. S. Aust., vol. 71, pt. 2, pp. 212—224. – 1949: Early Cambrian "Jellyfishes" of Ediacara South Australia and Mount John, Kimberley District, Western Australia. Trans. Roy. Soc. S. Aust., vol. 73, pt. 1, pp. 72—99. — Taylor, R., 1910: The Archaeocyathinae from the Cambrian of South Australia with an account of the morphology and affinities of the whole class. Mem. Roy. Soc. S. Aust., vol. 2, pt. 2, pp. 55—118, pls. I—XVI. — Whittard, W. F., 1953: The enigma of the earliest fossils. Proc. Bristol Natural. Soc., vol. 28, pt. 4.

THE MUSGRAVE MOUNTAIN BELT IN SOUTH AUSTRALIA

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Geosurveys of Australia Limited. Adelaide South Australia.

With two maps

Summary

Structural elements impressed upon the more easterly extensions of the Westralian shield were dominantly east-west features. These tendencies have channelled subsequent orogenies and geomorphic evolution, right down through the long history of the area.

Possibly two major anticlinal zones were devoleped along east-west zones, to be preserved to the present day as mountainous ranges and inselbergs. Massive batholithic intrusions mark the more southern zone, whereas outcropping rocks in the more northerly zone are predominantly metasedimentary. The granite zone is one of intense negative Bouguer anomaly (—150 milligals) indicating a strong density contrast between these massive granites of low density and the foliated granite gneisses of the northern chain. The strength of the earth's crust, locally, must be immense to support such unbalanced load, and yet deep grabens with inliers of Upper Proterozoic and Ordovician sediments flank the negative anomaly on both margins.

Since World War II, there have been outstanding advances in the geological knowledge of the more remote regions of South Australia. A modified approach to the understanding of many basic problems of Australian geotectonics is emerging from them.

The present geological summary contains an intentional bias towards geotectonics, as such understanding is vital to many problems of geosynclinical sedimentation and mountain building in central Australia, and to the geophysics of the earths crust.

Previous geological exploration in the "north-west" of South Australia was very limited but WILSON (1947) provides excellent valuable factual data of a petrological nature, concerning the eastern Musgrave Ranges.

I. Geomorphology

The north-west mountain belt in South Australia is part of a latitudinal province which extends also westward into Western Australia. Its overall length is about 500 miles. The Musgrave and Mann Ranges are a semi-discontinuous mountain chain some 300 miles long and 3000 to 5000 feet high. Other small ranges of lower altitude flank these to the south, but mostly they take the form of scattered hills and inselbergs in a desert topography.

The mountain valleys are all grossly overdeepened, and a complex of geomorphic cycles is evident. Valley plains lap abruptly against steep and rocky mountain walls and drilling for water reveals the buried valley floors sloping steeply to about 100—150 feet where they flatten to a subdued topography.

Plains surrounding the ranges are all considerably elevated, relative to Central Australian depressed areas, some of which, in the endorheic Lake Eyre Basin, extend below sea level. Plains elevations to 1500 to 2000 feet are general. The mountains are, without exception, surrounded by severe deserts with sand ridge systems well developed in parallel belts away from the Ranges, but confused about the mountain bases themselves where wind patterns are more complex.

Water courses flow only during floods, and few exist more than a few miles from the principal ranges. Only the Officer and the Hamilton maintain clear courses for greater distances. The Officer's gum-tree-lined channel of more than 100 miles has not flowed for more than the upper most 30 or 40 miles in white man's history. Underflow, however, is good, and as with most stream beds in these areas soakage waters can be obtained in digging to shallow depths, particularly behind rock bars.

In the extreme east, the Hamilton is the largest creek and drains a large area. It floods every few years and reaches Lake Eyre more than 300 miles away.

II. Regional Geology

The Musgrave Mountain belt is one of the oldest persistent mountain chains in Australia. An area of approximately 50,000 square miles appears to have been elevated more or less constantly from Proterozoic times onwards. This has been a principal source of sediment to surrounding and overlapping basins, and other low lying areas during most of subsequent time.

Upper Proterozoic, Cambrian (?) and Ordovician seas lapped its coasts, and they appeared again in Cretaceous time. Continued uplift and deep erosion have continuously exposed deeper cores of the old mountain systems, so that batholithic cores and granitised geosynclinal belts are now deeply exposed.

Glaciers enveloped the primitive mountains in Late Proterozoic times, and deep erosion following (?) Cambrian folding allowed epi-Cambrian and Lower Ordovician seas access to the foot of the remnant mountains.

Glaciation in the form of high level mountain glaciers again enveloped high altitudes in Permian times, with widely spreading periglacial debris in piedmont areas.

Cretaceous seas encroached on the area which at present is being deeply eroded.

1. Archaean Basement Complex

Pre-Cambrian rock complexes occupy most of the area. Granitised metasediments intruded by extensive suites of acid and igneous rocks form the bulk of the Musgrave and Mann Ranges, while the Everard-Birksgate Ranges to the south are principally granites and gneissic granites. The Tomkinson ranges consist of variously upturned blocks of basic and ultrabasic (?) lopolithic intrusives surrounded by granitised metasediments and granite. Dolerite dykes and sills in swarms are ubiquitous, but tend to be concentrated where middle Pre-Cambrian stresses are more strongly in evidence.

A. Stratigraphy

The Musgrave-Mann Ranges are pre-dominantly granitised metasedimentary complexes. Highly feldspathised and "granitic" quartzites persist for many miles to form prominent marker horizons within the Musgrave Ranges, along with granite gneisses of pelitic origin. Sedimentary structure can, in fact, be clearly observed throughout most of the Musgrave Ranges, in tight or simple fold structures, even though the hills are typically "granitic" on first impression.

Actinolitic and epidotic gneisses which are quite widespread in the eastern Musgrave Ranges, attest a more calcareous sedimentary environment, while bands of garnet gneiss (often with cordierite and spinel) form excellent marker horizons, particularly in the western Mann and the Tomkinson Ranges.

Altered quartzites figure prominently in the western developments of both ranges, and near Piltadi, in the eastern Mann Ranges, a drag-folded quartzite, completely resorbed to white "buck" quartz, forms a striking feature.

Many of the higher-grade gneisses, particularly of the Musgrave and Mann Ranges, are themselves of the charnockite type, but still preserve remnant sedimentary structure.

Gneisses of the Everard Ranges, and about Granite Downs are deeply granitised and their original nature is more obscure; a pelitic origin seems

most probable. It is notable that relatively richly allanitic gneisses are prevalent in the eastern extremity regions of both Musgrave and Everard zones. Lower-grade gneisses and schists have been found only in a small outlier west of the Everard Ranges, which may indicate a relatively shallower metamorphic situation, or collapsed roof pendant above the more deeply granitised mountain core, or a geologically younger remnant.

No stratigraphic succession has been decided in these provinces, although this will undoubtedly be attempted some day. Only near Erly Wanja Wanja Waterhole (southernmost face of Musgraves) is there sign of a possible unconformity within the "basement" complex, but the evidence is inconclusive.

B. Structure

Although the principal ranges are very obvious east-west striking geomorphic features, internal fold structures possess meridional axes where deformation is strong. This is normal for the ancient "Westralian Shield" of which this area is part.

Broadly, the metasedimentary structures of the Musgrave and Mann Ranges are remarkably simple, considering their deep geosynclinal burial. In the western Musgraves, for example, broad synclines and anticlines with limb dips from 5 to 10 degrees, pitch gently south. The resultant erosional topography tends to preserve synclines in outcrop, leaving the more deeply eroded anticlines as N-S "passes" through the towering ranges. Along the extreme south margin of the range, west of Mt. Woodroffe, south plunge usually steepens and beds skirting the range approximate east-westerly strikes, and dip 20 to 40 degrees towards the plains. This may be an influence of still later structural deformation (? Early Proterozoic).

Tight folding, frequently isoclinal, is characteristic only of the eastern Musgrave Ranges. This is a zone of intense deformation quite uncharacteristic of the ranges as a whole. Fold axes are strongly meridional, and as many as 5 major elongate anticlines have been recorded in a width of only eight miles in an extreme case (Kenmore Park). This folding is related directly to shearing movements between major sub-parallel transcurrent faults or thrust zones trending more or less W.S.W.-E.N.E.

The major fault systems of the Archaean basement trend slightly obliquely to the east-west direction. Principal directions, are, therefore, E.N.E.-W.S.W. and W.N.W.-E.S.E. respectively. Dolerite dyke swarms (see later) confirm this pattern, although in the granite belt (Everards etc.) additional sets of these trend almost exactly E.-W. or N.W.-S.E.

Both sets of faults in the metasedimentary mountain provinces involve considerable lateral translation. Those affecting the eastern Musgraves are zones of steep-angled overthrusting from the north, but with a shear component causing westward translation of the south block. There are at least two major zones of thrusting; viz. the Ernabella and Cuthbert thrusts separated by about 20 miles. Both are steep-dipping and between them lies the Tietkins Birthday Creek zone of isoclinal folding. In the over-

ridden block to the south of the Ernabella thrust, the two associated "Kenmore Park faults" appear to be "transcurrent" faults. They parallel the Ernabella structure, and an east-west shearing movement between these three elements is plainly visible. Numerous isoclinal folds developed in these intervening blocks have a strong en-echelon relationship reflecting the "south block-west" shear component mentioned previously.

Both the Ernabella and Cuthbert zones of thrusting are broad zones in outcrop, trending W.S.W.-E.N.E. and dipping steeply to the north. South of Ernabella, the zone of intense mylonitization, crushing, faulting and distortion occupies 2 to 3 miles in width. Dolerites, as the latest igneous phase, are variously affected by the movement, and tachylitic rocks associated with sills and dykes, and as shear invasions are ubiquitous. The Ernabella Thrust extends laterally for 50 miles whereas the Cuthbert and Kenmore zones are approximate about 20 miles in length. The Ernabella zone simply fades out in the west, but to the east appears to be truncated by a (?) vertical fault trending W.N.W.-E.S.E. in conformity with local dolerite dyke swarms.

Near Mt. Davies, the Giles basic igneous rocks occur in this province. Granitic rocks dominate in the Everard-Birksgate zone, but also occur extensively as isolated plutons and batholiths in the Musgrave-Mann zone. Basic to ultra-basic "bedded" lopolithic intrusions of the Tomkinson Ranges constitute the Giles Complex, while dolerite and gabbroid dyke rocks are common to all provinces.

C. Igneous Activity

1. The Granites, Charnockites and Pegmatites

Granitic igneous rocks, including charnockites, adamellites, granodiorites etc., form large scale intrusions throughout the whole mountain province. Generally the granites are not greatly stressed, and are remarkably fresh within a few inches of the surface.

The most extensive outcrops of acid plutonic rocks occur in the Everard Ranges. These are predominantly coarse-grained biotite or hornblende granites, adamellites, and granodiorites of "rapakivi" type, forming composite intrusions extending E-W for some 25 miles and over an outcrop width of almost 16 miles. A zone of fine to medium grained granites and granodiorites flank this on the east. Isolated hills extend at intervals to the Birksgate Range which appears also to belong to this phase of intrusion.

In the Musgrave-Mann granitised metasedimentary belt, similar granites intrude fold-axial regions, particularly the anticlines; mostly however, they are charnockites. The intrusions are generally elongated from north to south in conformity with axial trends, but many are irregular. Minor intrusions of norite, diorite, pyroxenite etc. are associated with these more acid rocks.

Pegmatites, although not uncommon, are mostly small and of the "dry" type possibly reflecting their great depth of origin in the mountain "core"

region. Numerous small pegmatites on the margins of the Ernabella charnockite carry orthite and thorite. Elsewhere small amounts of tantalite and beryl have been found in the rare "mica" pegmatites. (Sentinel Hill and Granite Downs.)

2. Giles Complex of Basic and Ultrabasic Igneous Rocks

Outcrops of these rocks are restricted to the Tomkinson Ranges in South Australia but extend almost 100 miles into Western Australia. Mt. Davies, Gosses Pile and associated ranges are disembered steeply-dipping layered sequences of a once continuous basic and ultrabasic composite (?) lopolith, separated by steeply dipping transcurrent faults. Some blocks are overturned, but originally the lower layers were generally more basic to ultrabasic. Only in Champ-de-Mars and Claude Hills to the north are remnants preserved which are flatlying essentially in "original situation".

Petrologically this great suite of rocks is typical of the Bushveldt basic-igneous complex of South Africa, which likewise is considered to be a composite lopolith. The rocks range in composition from ultrabasic (dunite, serpentinite, peridotite, harzburgite, pyroxenite, hypersthenite and troctolite) through basic (olivine gabbro, norite, leuconorite, etc.), to dioritic and anorthositic type. Contacts are mainly faulted, but wallrock is not uncommonly dioritic or gabbroic hornfels. Where contacts are undisturbed, igneous layering and enclosing metasedimentary structure may be concordant or steeply discordant.

Layering is particularly well developed in the Mt. Davies Range where there is a composite intrusion of harzburgites into earlier olivine norites. Some of these sills cross the pseudo-bedding structure. In general the ultrabasic rocks are the latest intrusives and concentrate near the base of the composite intrusives. Dunites are amongst the latest introduced material, and appear to intrude particularly along zones of major transcurrent fault dislocation.

While multiple-layering is the rule, some blocks show little of such variation over considerable thicknesses. The maximum measured thickness of a layered association, however, is almost 10,000 feet.

D. Mineralization

No important mineral deposits are known or have been worked in the whole of the area under review. Apparently the more volatile elements had been reconcentrated into zones now removed by erosion.

Traces of copper occur in association with basic igneous rocks and nickeliferous mineral occurs as a minor accessory in the Giles Complex. Non-economic amounts of galena occur in fault breccias near Moorilyana.

The radioactive minerals thorite and orthite occur in several small pegmatites along with some beryl and tantalite.

Precious opal in rich pockets has been gouged south of Granite Downs (Mintabie) but the field is small.

Silicate nickel (garnierite etc.) in fossil laterites, occurs widely about Mt. Davies, but in low concentration.

Gold was reported from near Gosses Pile late in the last century as "Earl's Find", and repeated prospecting expeditions to the area resulted in disappointment and often starvation. Violent arguments lead also to murders. That the find was in sacred aboriginal area added to the difficulties, as did drought and famine. The reputedly fabulous reef from which coarse gold allegedly was sampled in nuggets is a myth, although the formation described by Earl is now known. Unfortunately the story was "borrowed" by Lasseter whose epic dashes into the desert are now legend. Many people suffered financial loss because of these ill-based beliefs in "rich gold for the taking" but the fraud dies hard.

2. Upper Proterozoic Rocks

Proterozoic rocks are restricted in outcrop to an area north and south of Granite Downs, but also in a small inlier immediately south of the central mass of the Musgrave Ranges.

A. Stratigraphy

Pre-Ordovician glacial tillites and periglacial boulder beds and conglomerates, with soled and facetted glacial erratics are present in widely separated areas about the range. They are associated with well bedded sandstones and quartzites, overlying laminated slates and thin limestones, and occur marginal to Archaean blocks in the low ranges west of Granite Downs. These are undoubtedly the equivalents of the Sturtian series of the Denison Ranges, extending from these Ranges almost 1,000 miles to the south-east, to and beyond Adelaide.

Total thicknesses of more than 10,000 feet are indicated and more than one tillite is present. Boulder beds near Moorilyana attain several thousand feet in thickness, apparently as a terminal moraine, and locally the lower tillite is in basal contact with the Archaean igneo-metamorphic complex. In general, these boulder trains wedge out very rapidly from the Archaean into conglomerate or thin, water-laid, glacio-fluvials. In these areas earlier-deposited basin infillings such as well-bedded quartzites and grey slates are present. As about Mt. Painter and Radium Hill in the Adelaide Geosyncline, block faulting about the Basin margins appears to have brought about the uplift which permitted stripping of earlier-laid Proterozoic sediments, which were redeposited with the glacial debris. Hence quartzites, and other sedimentary rocks, feature prominantly in some local tillites. Also, as with the Mount Painter faulting, basic lavas were in active eruption just prior to severe glaciation, and these flows immediately underly massive tillites in the Indulkana Ranges.

A remarkable geomorphic feature of the local tillites is the unusual induration with causes them to weather more like granites, in large spheroidal masses. These exfoliate in sheets with complete disregard of the vast differences in composition of the contained heterogenous erratics

and ground mass. This is well seen at Moorilyana, but nowhere better exemplified than in Mt. Olga and Ayers Rock just across the State border in Northern Territory. In all these "Sturtian" outliers a complete museum of local rock types can be viewed in any small sample area.

The many thousands of feet of laminated slates and calcareous slates and limestones are quite characteristic of the Tapley Hill group overlying Sturtian tillites near Adelaide. These are followed by purple and brown slates with dolomites, which may be the Marinoan equivalents. Apparently comparable (?) Marinoan red beds extend south for more than 200 miles as recently demonstrated in shallow borings. These would appear to completely enclose the Ordovician sediments described in the next section.

B. Structure

Upper Proterozoic sediments are folded steeply with prominent east-west axes. A tendency to closed structures is evident south of Granite Downs, and generally limbs are steep.

Near Moorilyana thick glacial boulder beds have been infaulted between two sets of block faults trending slightly north to west. The Granite Downs Archaean "horst" lies to the south of this segment, and is again bounded by downfaulted Proterozoic to the south.

C. Igneous Activity

Proterozoic sediments are entirely unmetamorphosed in the area, except for the minor effects of faulting and folding. They have suffered no igneous intrusions except for very minor local basaltic outpourings as in the Indulkana Ranges, where amygdaloidal lavas were extruded contemporaneously with the onset of Sturtian glaciation. A sequence of flow basalts and tuffs, partly as submarine intrusions, immediately underlies the earlier tillite. The basalts are highly vesicular, and some carry very minor copper mineralisation. The extrusions appear to have been quite local, and wedge out completely from 200 feet thickness in about one mile. Basaltic erratics in neighbouring tillites reflect contemporary erosion.

3. Ordovician

A trough of marine sediments referable either wholly to the Ordovician or in the lower part also to the uppermost Cambrian, surrounds the mountain province along its southern border. This has features in common with the Amadeus trough to the north near Alice Springs, but also certain noticeable differences. Both are markedly east-west alongated basins, and both tend to shallow abruptly to the east (in present-day development) where they give way to Proterozoic outcrops. However, whereas the Amadeus Ordovician is only gently transgressive, on to underlying Cambrian formations, the present formation is in strong structural non-conformity with the underlying Proterozoic, and the Cambrian was completely removed, if ever present.

A. Stratigraphy

Well bedded sandstones more than 5,000 feet thick surround the Musgrave Mountain belt on the south, from Granite Downs to and beyond the Western Australian border — a distance of almost 300 miles. These are even-grained and cross-bedded, and at least two limestones, several tens of feet in thickness, occur short distances above the base. The basal sandstones rest with marked angular unconformity on a near perfect base-surface. They are fault-folded into Adelaide System sediments, and also extend onto Archaean basement.

In basal members, vertical worm tubes *(Scolithus)* are very common, but no other diagnostic fossils have been found. Doubtful *Scolithus* appear at the top of the Lower Cambrian of the Amadeus basin to the north, and extend well into the Ordovician.

A feature of the lower sandstone members of the Indulkana Range is the complex intraformational folding in the form of internal overturning or "recumbent folds". These suggest slumping to the south. Associated sedimentary members are steeply cross-bedded, indicating a shallow water environment.

B. Structure

Mostly the sediments exhibit gentle dips to the south, away from the Musgrave block, but locally dips may be steep to vertical. The sediments occupy an east-west elongate trough which closes off near Mt. John. A synclinal outlier forms the Indulkana Range near Granite Downs, and still further east, a steep dipping synclinal limb plunges beneath the Alberga plains (not shown on map).

Airborne magnetometer traverses from near Eucla to the base of the Everard Ranges confirm the broad trough structure, and support the contention that Adelaide System rocks occur widely beneath the deserts to the immediate south.

4. Cretaceous (?)

Basal sandstones, grits and cut-and-fill conglomerates lense and wedge in overlap onto the older rock both from the east and south. To the east they merge into the increasingly thick Cretaceous marine shales which comprise a major formation of the Great Australia Artesian Basin. The Aptian pelecypod *Maccoyella barklyi* occurs sparingly in some of these shales.

Similar beds skirt the south of the range country, but no fossils have been recorded in them.

III. Geotectonics

The north-west mountain belt, because of its excellent rock exposure offers outstanding opportunities in the elucidation of Pre-Cambrian geotectonics. Weaknesses imparted to the rocks during these ancient eras have effectively channelled later crustal failure, and affected folding of the overlying sediments.

A. Archaean Structural Development

The original folding of Archaean sediments in this province was predominantly under influence of N-S confining pressures. Deformation was quite gentle, resulting in broad structures with east-west elongation.

Granitisation of the metasediments, and complex batholithic intrusion at deep crustal levels, occurred regionally. Charnockites and related intrusives into thick metasediments seem to have been restricted to a more northerly belt enclosing the Musgrave and Mann Ranges which confirm the original east-west element in folding. Massive hornblende and mica granites on the other hand make up almost the entire Everard-Birksgate zone to the south.

Late in this period of orogeny steep overthrusting or reversed faulting occurred in the eastern Musgrave region. The zones of intense movement were directed E.N.E.-W.S.W and, in view of the straight strikes even in mountainous topography, shear planes are assumed to have been steep. Most of the shears dip to the north, and there is a marked tendency to transcurrent movement with the south-block translated westward. Four such sub-parallel zones are clearly defined, and the largest — the Ernabella shear fault — is 50 miles long. Metasediments sandwiched between the faults are deformed into tight isoclines, often with adjacent fold axes at one to two mile intervals. In the Kenmore Park area the folds exhibit en-echelon relationships due to the W.S.W.-E.N.E. shearing component (transcurrent). The isoclines may have originated under the influence of earlier folding tendencies, but were greatly intensified during the transcurrent shear-faulting. More of an obliquely east-west element seems now to have been impressed on the area. Fracturing of the granitic masses now developed along several well defined and preferred directions.

In the batholithic Everard-Birksgate zone, the major directions of fracture-failure, in order of intensity, are as follows:

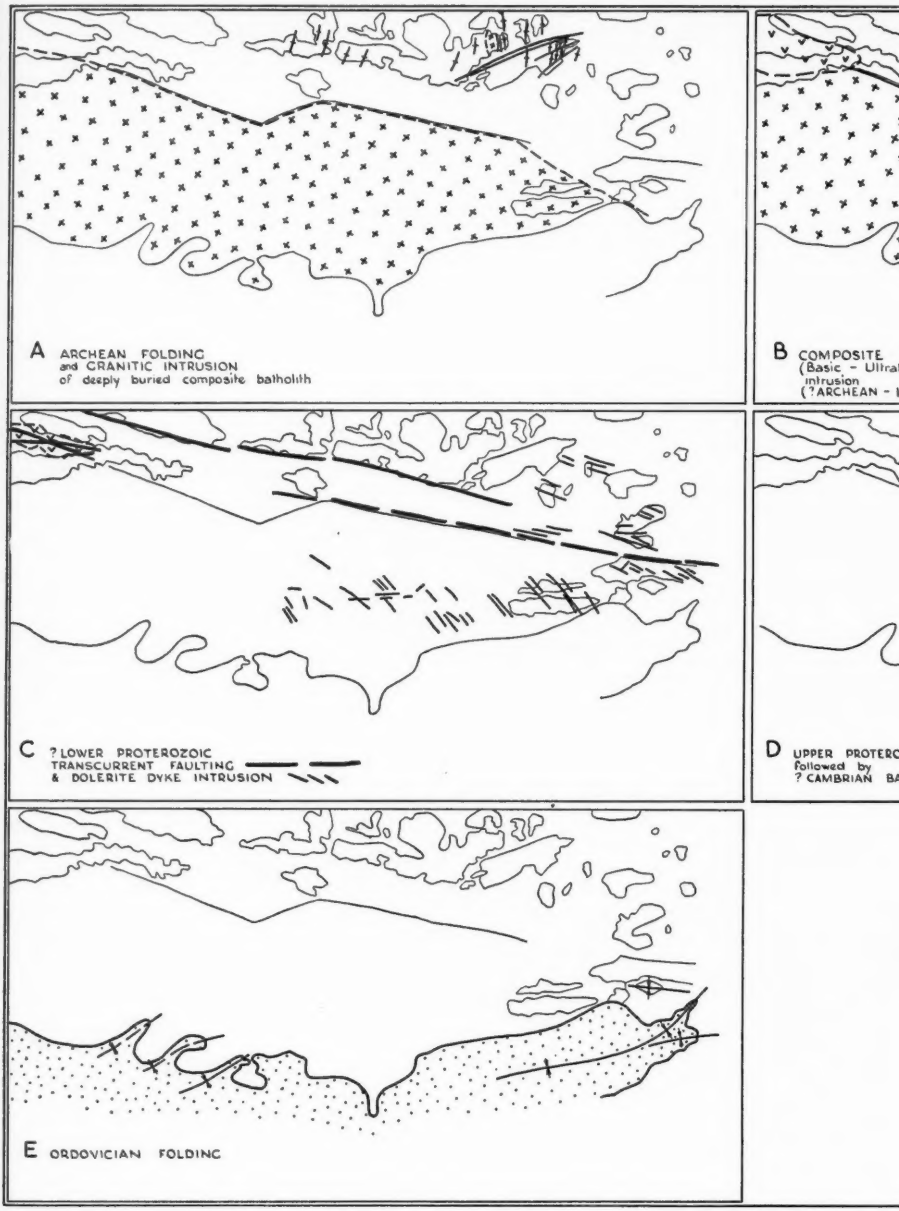
N.W.—S.E.
E.—W.
W.N.W.—E.S.E.
N.E.—S.W.

In the Musgrave Ranges the relative directions are:

W.N.W.—E.S.E.
E.—W.
E.N.E.—W.S.W.
N.E.—S.W.

A more east-westerly fracturing tendency is therefore apparent in the metasedimentary zones, suggesting shallow crustal failure influenced by the relief of north-south directed stresses.

During latest Archaean times, or the early Proterozoic, upwellings of basic and ultrabasic igneous material occurred, apparently preferentially along fractures of the W.N.W.-E.S.E. or E.N.E.-W.S.W. association. These lay along a strongly east-west trend and most of these intrusives occur about latitude 26 degrees S. (from Ernabella via the Tomkinson Ranges into Western Australia). A deep crustal zone appears to have been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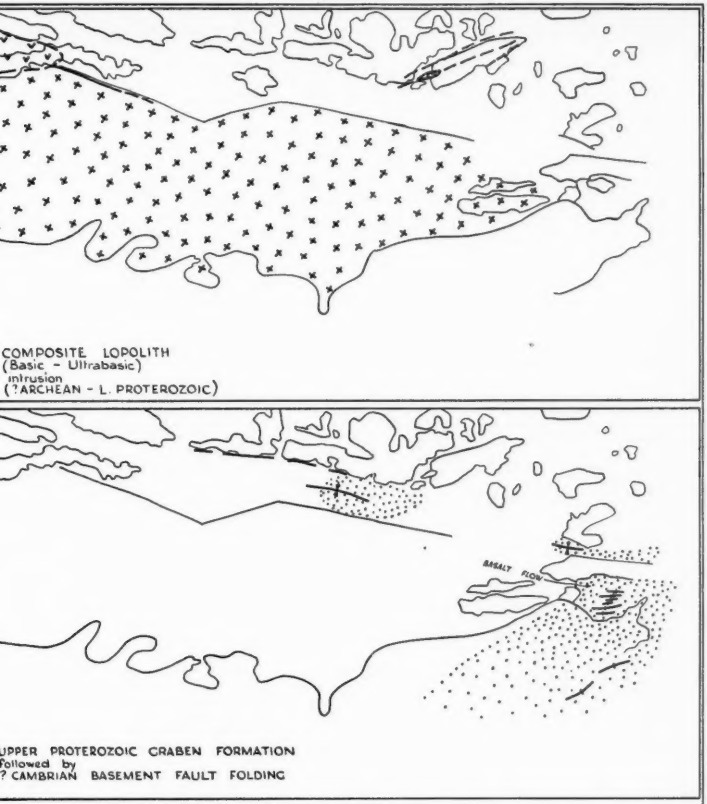
? CAMBRIAN BA
E ORDOVICIAN FOLDING



STRUCTURAL EVOLUTION
OF THE
MUSGRAVE MOUNTAIN PROVINCE
SOUTH AUSTRALIA

SCALE 0 32 64 96 MILES

under stress "latitudinally". Upwellings of these basic magmas continued to develop widespread layered lopoliths at medium or shallow crustal levels. Presumed contemporaneous volcanic activity at the surface, as evidenced by occurrences across the W. A. border and by widely distributed erratics in Sturtian tillite, suggests that the less basic differentiates of these crystallizing magmas escaped extensively to the surface.

Late-stage crustal movements along an W.N.W.-E.S.E. zone caused injection of more ultrabasic magma into the new composite lopoliths to be followed by intense deformation, tilting, folding and transcurrent faulting. The greatest movement occurred along a latitudinal zone, along an interplay of oblique shear zones of the E.-W. and W.N.W.-E.S.E. association.

Transcurrent fault movements along these planes would have favoured re-opening of earlier fractures with subparallel preferential tendencies such as E.-W., W.N.W.-E.S.E., and N.W.-S.E.

These and, to a lesser extent, other planes of fracturing were subsequently invaded by dolerite-gabbroid dyke rocks. The dykes invaded all known pre-Upper Proterozoic rocks in the area, and mark the close of a prolonged era, or eras, of intense compressive stresses on the newly welded increment to the continental shield.

Gravity Observations

Although gravity observations have been made only across the eastern extremities of the Musgrave and Everard Ranges, one significant factor emerges very clearly. The Everard-Birksgate zone of massive granite intrusion is a belt of intensely negative Bouguer anomaly. The anomaly which exceeds 150 milligals is considered to be due to direct contrast in density between these massive granites of low density, and the foliated granite-gneisses typical of the Musgrave-Mann Ranges Archaean complexes generally.

This is in direct contrast to other outcropping Pre-Cambrian areas in South Australia where the Bouguer value is generally small and positive. A comparable belt of extreme negative anomaly has recently been described by M. J. Innes in Central Quebec where massive granite intrusion is presumed to have accompanied late Pre-Cambrian mountain building.

Retention of these large anomalies for great periods of geological time poses interesting problems as to the strength of the earth's crust and interior, and why the masses responsible for the gravity disturbance have not been eliminated in the far distant geological past, by uplift and erosion. Obviously it would seem, the strength of the earth's crust in Pre-Cambrian shield areas was capable of supporting great unbalanced loads without isostatic adjustment, such as occurs in younger mountains.

B. Upper Proterozoic Structure

The onset of the late Proterozoic saw further definition of east-west structural elements established in the Musgrave mountain belt. Two subparallel mountain chains had developed with a zone of potential crustal

weakness and transcurrent faulting separating them. Block faulting may have enhanced mountain elevation, and the mountains themselves continued to be a major source of sediment supply, nurturing important mountain glaciers during the Late Proterozoic Era. Seas surrounded the mountain chains and invaded the intermountain "low" between them. Basaltic volcanic activity immediately preceded glaciation and the escaping lavas may have issued by faults bounding local crustal mountain blocks.

Some 10,000 feet of sediments accumulated in Sturtian times, and strong deformation occurred probably during the Cambrian period. Block faults with east-west or W.N.W.-E.S.E. strike tendencies were active, and controlled the folding which developed with markedly east-west axes. Basement horsts (e.g. Granite Downs) controlled the broader anticlines or anticlinoria, and grabens cradled the synclines or synclinoria; a series of subparallel folds with steeply dipping limbs were developed through this mechanism. Uplift, deep erosion and finally peneplanation were well advanced by Ordovician times.

C. Ordovician Structure

Crustal downwarping, possibly assisted by graben faulting, provided access for Ordovician seas. Much of the negative zone south of the Everard Ranges, previously occupied by Upper Proterozoic seas was again inundated. The strongly east-west alignment of the fold basins is completely preserved, and the measure of local basement block faulting is apparent from the abrupt change from flat dips to steep and sometimes vertical disposition of major fold limbs.

Acknowledgements

The geological investigations basic to this work were carried out by the authors originally as officers of the South Australian Geological Survey and later during various economic exploration projects operated by Geosurveys of Australia Limited on behalf of clients.

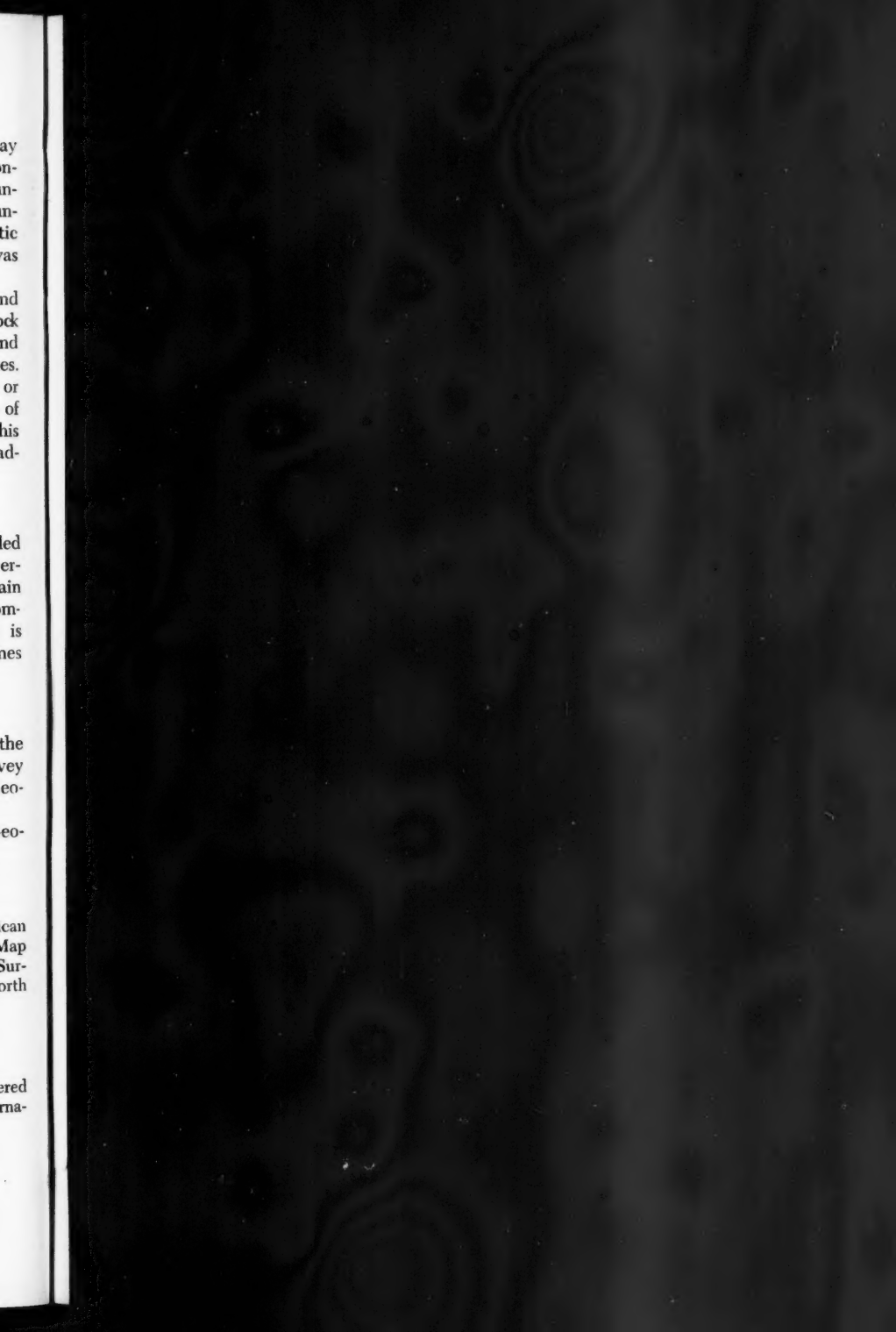
Permission to publish information gained while officers with the Geological Survey is greatly appreciated.

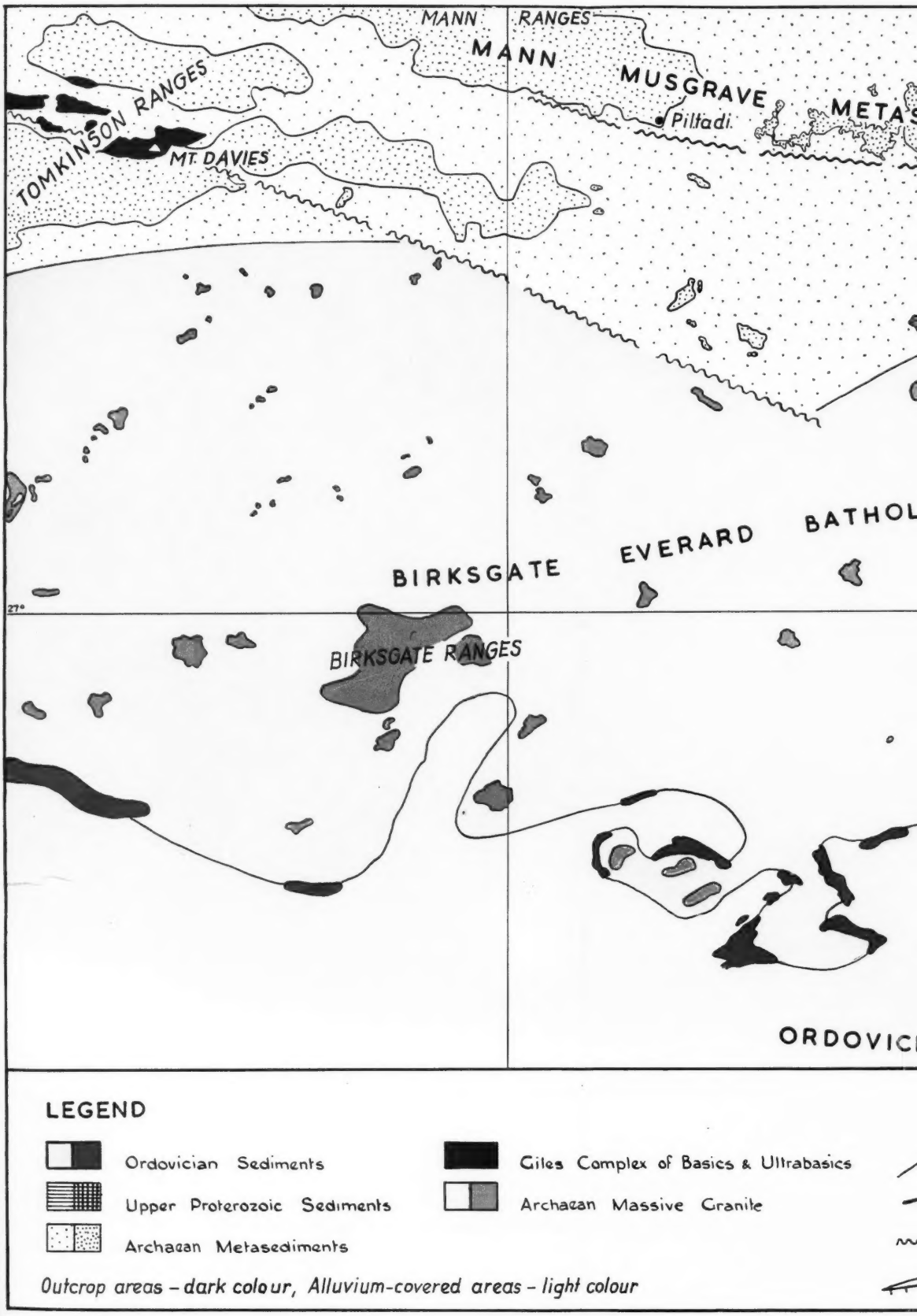
References

Innes, M. J. S., 1957: Gravity and Isostacy in Central Quebec. American Geophysical Union 38 (2). — Sprigg, R. C., and Wilson, R. B.: Geological Map sheets "Indulkana", "Kenmore", "Giles" and "Ernabella". S. A. Geological Survey. — Wilson, A. F., 1947: The Charnockitic and Associated Rocks of North Western South Australia. Trans. Roy. Soc. S. A. 71.

Errata

On the accompanying coloured map, the meridians should be numbered 130° to 133° and the black circle S. of Mt. Cuthbert should be marked "Ernabella".




130°
MANN RANGES
MANN
MUSGRAVE
Piltadi
META
TOMKINSON RANGES
MT. DAVIES
BIRKSGATE
EVERARD
BATHOL
27°
BIRKSGATE RANGES
ORDOVICI
LEGEND
Ordovician Sediments
Upper Proterozoic Sediments
Archaean Metasediments
Giles Complex of Basics & Ultrabasics
Archaean Massive Granite
Outcrop areas – dark colour, Alluvium-covered areas – light colour

Fold axes

Dolerite dykes

Major Faults

Thrust Zones

MUSGRAVE MOU
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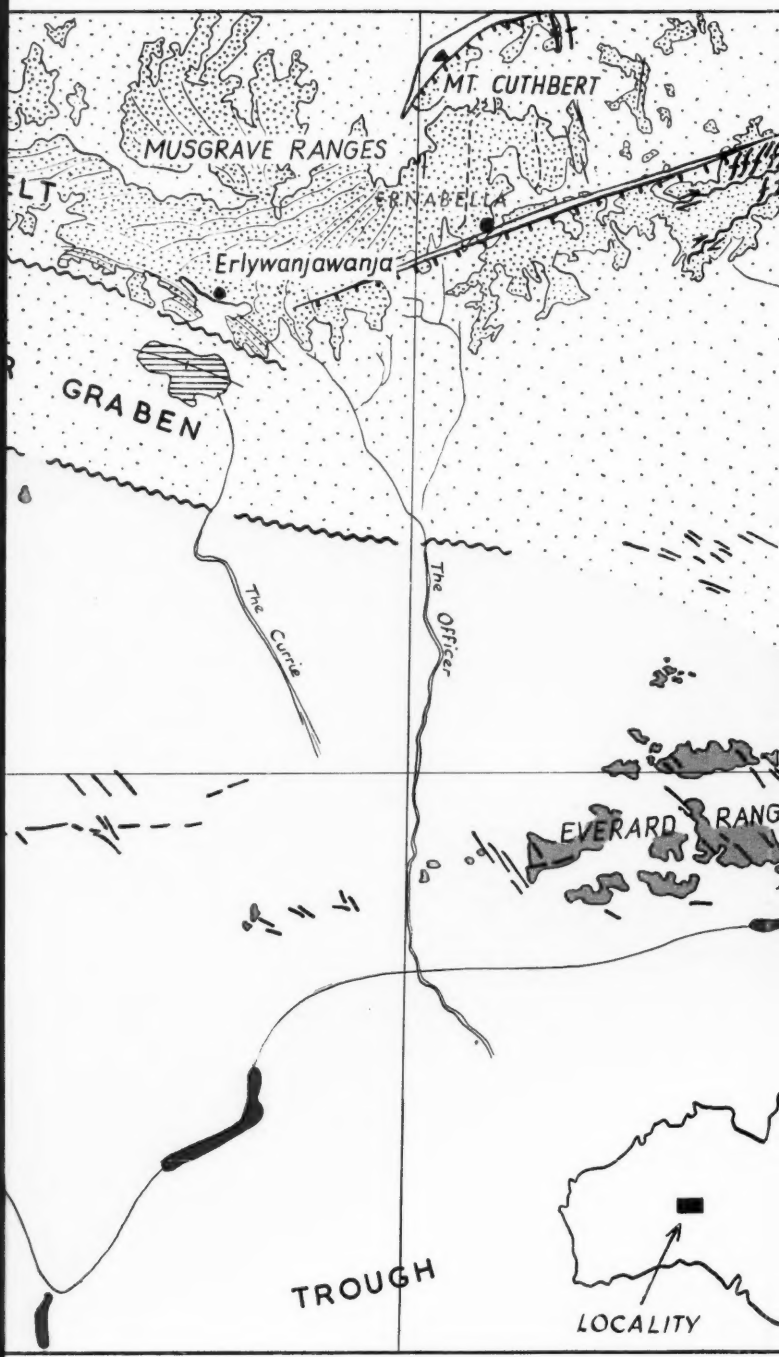

MUSGRAVE MOUN
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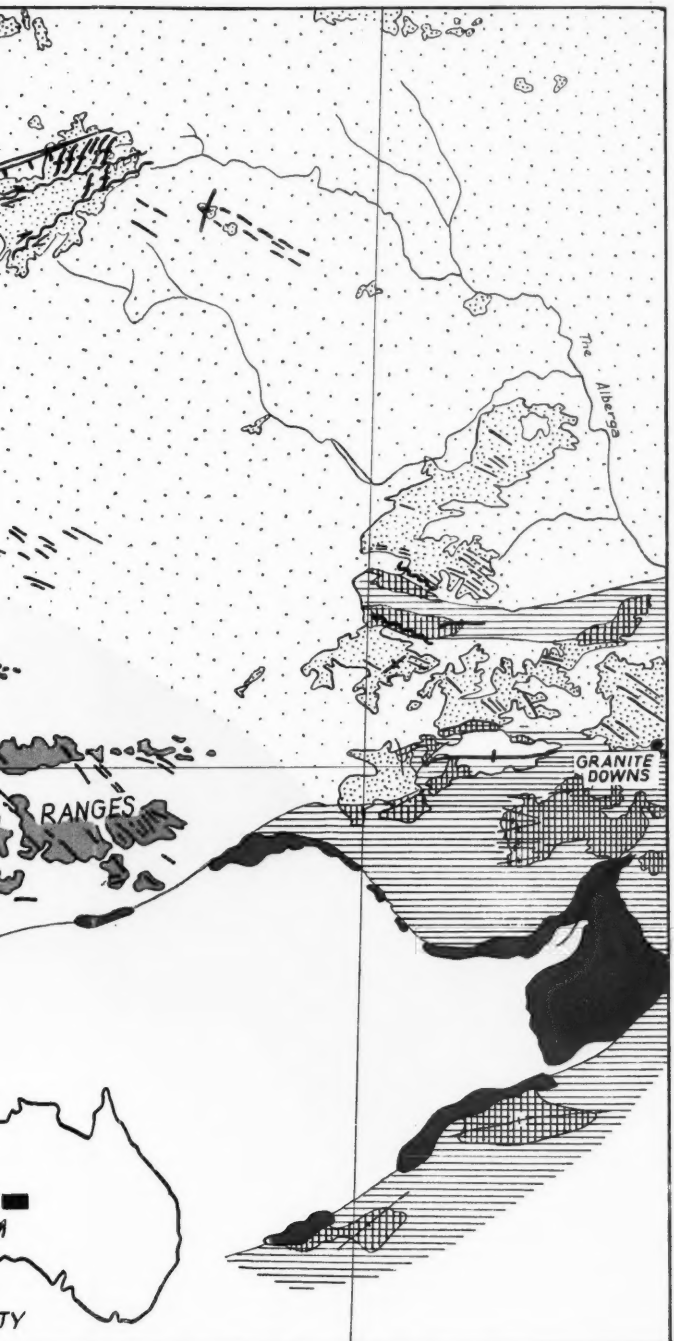

MOUNTAIN PROVINCE
H AUSTRALIA
SHOWING
RUCTURAL FEATURES

6 32 48 MILES

CAULDRON SUBSIDENCES, GRANITIC ROCKS, AND CRUSTAL FRACTURING IN S. E. AUSTRALIA

by E. SHERBON HILLS, *University of Melbourne*

With 9 Figures

Abstract

The structure and history of several Devonian cauldron-subsidences and related granitic intrusions showing evidence of sub-surface ring-fracturing in South Eastern Australia are discussed. The Marysville Igneous Complex includes fish and plant bearing beds in the Acheron Cauldron, which has a diameter of 15 miles, and contains 6000 ft. of acid lavas, with subordinate andesites and basalts. Most of the occurrences are consanguineous. The parent magma is intermediate, close to the hypersthene dacites of the region, and is believed to have been injected as a magma wedge from the east.

The great mobile belt of eastern Australia, some 200 miles wide and 2500 miles long as it is now known on the Australian continent itself, is one of the most persistently active zones of the earth. Omitting the doubtfully pre-Cambrian, but certainly very old rocks of northern Queensland, the belt yields a record of almost continuous if sporadic mobility and magmatism from Cambrian to Recent times. Marine and fresh water sediments, volcanic rocks, dyke swarms and plutons may now be dated with reasonable reliability, and many regions have been rather intensively studied, especially in Victoria and New South Wales where detailed mapping was begun a century ago. The south-east of Australia affords an unrivalled field for the study of the relations between magma and tectonics, some aspects of which, and particularly the cauldron subsidences and granitic rocks of lower and middle Palaeozoic age, are the main topic of this paper. It should be pointed out, moreover, that in addition the region affords a wide range of igneous suites of types such as are currently recognized in relation either to petrogenesis or to tectonic setting. Among these may be mentioned those that have been the subject of detailed study, and particularly therefore the Cambrian submarine basic lavas and tuffs with interbedded sponge-bearing cherts and shallow marine fossiliferous mudstones of the Heathcote belt, Victoria (SKEATS, 1908); the very similar Devonian submarine basic lavas, keratophyres, tuffs and cherts of the Gloucester and nearby districts of New South Wales (BENSON, 1913—1918); the continental basaltic suites of Cainozic age in the Highlands of Victoria, New South Wales and Queensland (EDWARDS, 1938; BROWNE, 1933), and the closely associated but probably tectonically distinct alkaline volcanic complexes; the serpentine belts associated with Palaeozoic tectogenes in New South Wales and Queensland (BENSON, 1913—1918). DAVID (ed. BROWNE, 1950) affords a convenient reference book on these and many other suites which are known in good petrological and structural detail, and it is, indeed, a practicable proposition to begin the attempt at a synthesis of magma and tectonics for the whole region,

taking that much neglected factor in petrogenesis — time — into account. This paper, however, deals with one major aspect of the numerous and widespread acid igneous complexes of the south-east, which has not previous been discussed in the literature.

Recognition of Ring Complexes

The region under consideration forms part of the South Eastern Highlands of Australia and the igneous complexes lie for the most part at elevations of from 2000 ft. to 6000 ft. above sea level, in deeply dissected and heavily forested mountains to which access is still not easy. Some of the massifs in Victoria have been known petrologically though not structurally through the work of Skeats (1910), Skeats and Summers (1912), Morris (1914), Junner (1915), Summers (1923), Edwards (1932 a, 1932 b, 1956), and others on the central Victorian Devonian dacite suite in which hypersthene dacite is the most characteristic rock-type, although a variety of intermediate and acid lavas is, in fact, present in the assemblages (see Fig. 1). The discovery of fresh-water fishes (*Bothriolepis*, *Phyllolepis*, *Dipterus*) in strata interbedded with such a lava series at Taggerty (see Fig. 2) first established the Upper Devonian age of these lavas, and, presumably of their close petrological analogues in nearby areas (Hills, 1931, 1932). A few years later the notion occurred to me that one such lava sequence, some 150 sq.miles in extent and including the occurrences at Taggerty, might have the structure of a cauldron subsidence with a surrounding ring-dyke. This working hypothesis has been tested by personal mapping of the whole complex during the past 20 years, during which it has been completely established, and substantiated by more detailed local surveys of sectors carried out by State authorities (Thomas, 1947). The cauldron is part of the much larger Marysville Igneous Complex which has been found to contain two major cauldron collapses and other distinct petro-tectonic units [1]) (see Figs. 1 and 2).

One of the implications of the recognition of cauldron subsidences of such great size is that others should be represented in the co-magmatic region, which is known to be of great extent. Consequently a study of the Violet Town Volcanics, part of the Strathbogie granite-lava Complex, was arranged (White, 1954) and this in turn has been found to possess a quite similar group of rocks, indeed astonishingly similar in view of that fact that we have to deal only with variations on a limited theme of acid lavas and intrusions. Cauldron subsidence is again revealed, but with a polygonal rather than arcuate or elliptical pattern of fractures. Several other areas which have been partially or completely mapped are discussed herein, some with lavas indicative of cauldron collapse, others composed of granite or granodiorite with elliptical or polygonal outlines and some indication of internal structure which bears on their mode of emplacement.

[1]) A monographic account is in course of preparation by the author.

The Marysville Igneous Complex

The Marysville Complex is shown in its regional setting in Fig. 1. The basement is Silurian and Lower Devonian marine arenaceous and argillaceous sediments, strongly folded about NNW axes. A dyke-swarm, chiefly

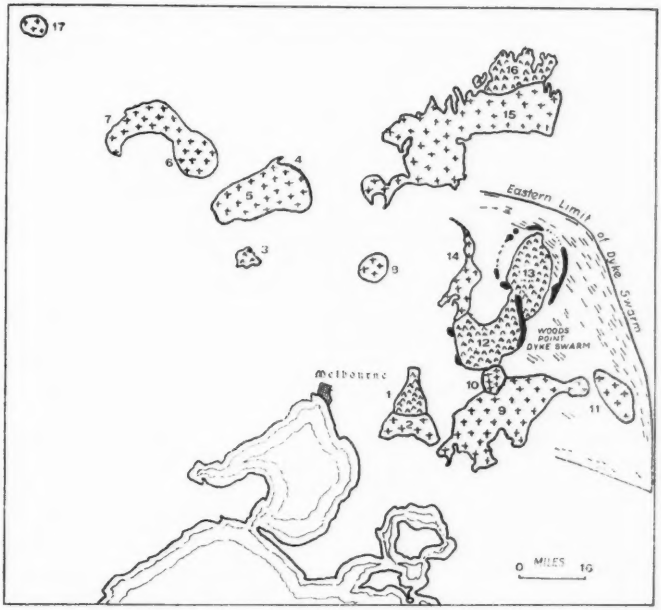

Fig. 1. Distribution of hypersthene-dacite suite of lavas and some related granitic rocks in central Victoria. Localities referred to in the text as follows: 1. Dandenong Ranges volcanics. 2. Lysterfield granodiorite. 3. Mt. Macedon hypersthene dacite. 4. Pyalong granodiorite (part of 5, Cobaw granodiorite). 6. Harcourt granodiorite. 7. Maldon granodiorite. 8. Mt. Disappointment. 9. Tynong granite. 10. Warburton granodiorite. 11. Baw Baw granodiorite. 12. Acheron Cauldron. 13. Cerberean Cauldron. 14. Black Range granodiorite. 15. Strathbogie granite. 16. Violet Town Volcanics. 17. Mt. Kooyoora granite.

of lamprophyres and quartz-diorites — the Woods Point Dyke Swarm (JUNNER, 1920; HILLS, 1952) — is dispersed throughout the region, but is sharply terminated along a defined line on the west. These dykes are either late Middle or early Upper Devonian in age, and they show evidence in the faulting that affects them of the persistence of orogenic stresses after their intrusion, which was most probably a very rapid event. Because of the obvious space relationship of the dyke swarm and the Upper Devonian Marysville Complex which unconformably overlies the folded basement rocks and the dykes, a possible magmatic relationship may be suspected

and accordingly the chief rock-types of the swarm are listed, although this topic will not be further discussed herein.

Rock Types of the Woods Point Dyke Swarm
(Hills, 1952)

Ultrabasic	Basic	Intermediate	Acid
Peridotite	Gabbroporphyrite	Hornblende-diorite-porphyrite	Quartz-porphyry
Perknite	Meladiorite	Quartz-diorite-porphyrite	Quartz porphyrite
	Melamonzonite	Quartz-diorite	Granophyre
	Olivine Basalt		
	Basalt		

Lamprophyres —

Kersantite (most frequent), minette, camptonite, spessartite.

Resting on an eroded, but by no means planated surface of the older rocks, are the sediments and lavas of Upper Devonian age, all of which now lie entirely within the confines of the cauldron subsidences. In addition the complex includes granodiorite, adamellite and granite massifs and a variety of acid and intermediate dykes, the more significant of which are ring-dykes of granodiorite-porphyrite. Two major cauldron subsidences are present, the Cerberean Ring-Cauldron with a diameter of 15 miles and a surrounding ring dyke which is separated from the lavas by erosion, and the Acheron Cauldron, of more complex structure. The plutons include the Black Range Granodiorite, a great arcuate intrusion on the west; the Warburton Granodiorite, a polygonal intrusion with notably straight margins; the Tynong Granite, a great irregular mass to the south; and the Baw Baw Granodiorite, a separate elliptical mass to the east. The general succession of stratified rocks in the two cauldrons is listed below.

Upper Devonian Sequences

	Cerberean Cauldron		Acheron Cauldron
	2a. "Snobite" hybrid		4. Hypersthene dacite
Cerberean Volcanics	2. Biotite-rhyodacite with hypersthene in places		3. Hypersthene-biotite rhyodacite
	1a. Toscanite	gradation	2. Biotite-dacite / Quartz-dacite — variants
	1. Nevadite		1. Nevadite
Taggerty Group	3. Fragmental acid volcanics (ignimbrite)		—
	2. Basic volcanics (basalt, andesite)		Andesite xenoliths in later flows
	1. Shales and sandstones with fish and plant remains		—
Snobs Creek Volcanics	3. Biotite rhyodacite		—
	2. Rhyodacite		—
	1. Rhyolite		soda rhyolithe (Warburton)

Basal Conglomerate

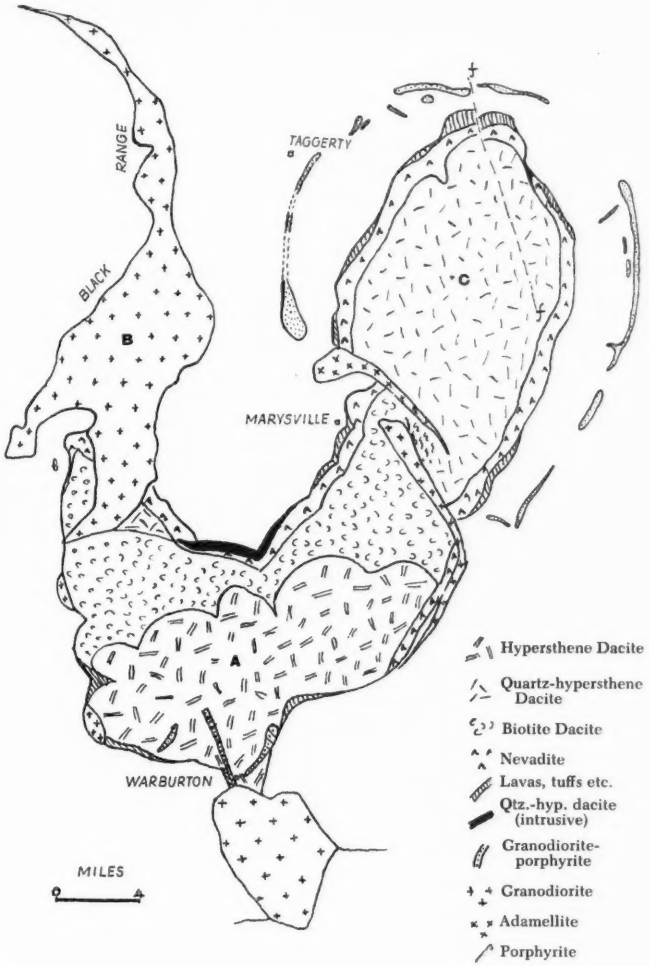

Fig. 2. Cauldron subsidences of the Marysville Igneous Complex: A. Acheron Cauldron; B. Black Range Ring Dyke; C. Cerberean Cauldron. (Based on mapping by officers of the Geological Survey of Victoria, Junner, Edwards and the author.)

From the sequence, rock types and structure of the cauldrons it is possible to read their history with some conviction. The Snobs Creek Volcanics and the Taggerty Group are consistently found within the Cerberean Cauldron but not in the Acheron [2]), for which reason it appears that it was early movements of subsidence in the Cerberean ring, accompanied by the first volcanic outbrusts, that gave rise to the depressions in which the lacustrine fish beds, with associated plant remains, were deposited. This preliminary subsidence apparently lasted a long time while lacustrine deposition went on, but eventually thin andesites and basalts accompanied by tuffs were extruded and sedimentary deposition ceased. These volcanics were doubtless extruded from central vents, but their necks have not been discovered. The initiation of the final collapse of the cauldron was marked by a widespread acid ignimbrite. Immediately following and without intervening weathering is a great cataclysm of acid lavas some 3000—4000 ft. thick which undoubtedly indicates the sudden collapse of the central block. At the base is a rhyolite (nevadite), with phenocrysts of quartz, perthitic orthoclase, cordierite and subordinate biotite and plagioclase. Grading upwards, this becomes progressively richer in biotite and plagioclase and in places passes to toscanite (s e n s u l a t o), and then further to biotite rhyodacite with subordinate hypersthene and almandine, cordierite disappearing during these progressive changes. At the northern end of the Cerberean cauldron, however, biotite nevadite is overlain directly by the rhyodacite. The highest parts of the lava succession are seen about Mt. Torbreck and Lake Mountain at elevations of between 4000 and 5000 ft. They consist of biotite rhyodacite with a large proportion of included blocks of leucocratic quartz porphyry and of garnetiferous granodiorite porphyrite. These inclusions are very obvious on weathered surfaces and the rock was originally mapped as granite (Geological Map of Victoria, 1902). Dips in the lower members of the succession range from 25° to 34°, but these were measured at the present edge of the Upper Devonian sequence, which is some 2—5 miles from the ring-dyke. The Cerberean Cauldron thus has a basin structure, complicated on the south where it intersects the Acheron Cauldron, but elsewhere affecting all the rocks up to and including the nevadite. Above this dips cannot be measured.

The ring dyke surrounding the lava dips outwards at 75°—80°, and a stratigraphical measure of the throw is available from the mapping of the Silurian bedrock (Thomas, 1947). This is 2000—3000 ft., but as the rocks are strongly folded and not highly fossiliferous the throw cannot be precisely determined in this way. Perhaps of greater significance is the total thickness of bedded rocks in the cauldron — some 5000—6000 ft., the Cerberean Volcanics alone aggregating more than 3000 ft. in one or two great flows. The rock of the ring-dyke is chiefly a garnetiferous granodiorite-porphyrite exactly comparable, except for the absence of hyper-

[2]) Small outcrops of soda rhyolite at Warburton (Edwards, 1932 b) may perhaps be an exception.

sthene, with the biotite rhyodacite among the lavas. Chilled edges of the dyke are, moreover, very fine-grained cordierite quartz porphyry, clearly the equivalent of the nevadite. There is thus no doubt as to the source of the Cerberean Volcanics. They were the last extravasations from the ring dyke. However, no definite sources of eruption from the other lavas, or traces of equivalent types in dykes, have been recognized.

The Acheron Cauldron

The structure of this cauldron is that of a flap hinged in the north and sinking towards the south. The uppermost flow, a quartz-free hypersthene dacite, is widespread, but its thickness varies as it wedges out to the north and thickens to the south, filling the tilted cauldron. This flow is in all ways similar petrologically to the other well-known occurrences of hypersthene dacite described from the Upper Devonian of Victoria (Skeats, 1910; Morris, 1914; Summers, 1923; Edwards, 1956). Erosion has not proceeded so far in the Acheron Cauldron as in the Cerberean, and the intrusions of granodiorite and granodiorite-porphyrite along its edge are still in contact with the lavas. The flows beneath the hypersthene dacite are comparable with the Cerberean Volcanics, that is biotite dacite and nevadite, but over most of the cauldron there are no lower sediments or lavas, thus suggesting that this cauldron developed somewhat later than the Cerberean. It will be seen too that the outline combines arcuate fractures (on the east) with straight fractures (on the west and south).

Plutons

The third unit of the complex is the Black Range Granodiorite, a curving intrusion broadening to the south, and which I interpret as a ring dyke splitting towards the south into two arms separated by a bedrock mass. No lavas appear to be directly related to this ring dyke.

True plutons are restricted to the area south of the Acheron Cauldron. They include the Warburton Granodiorite, a polygonal massif which makes contact with the hypersthene dacites at Warburton and metamorphoses them; the very large irregular Tynong granite massif, and the elliptical Baw Baw granodiorite. Along the contact of the Tynong granite and the Warburton granodiorite large blocks of Silurian bedrock are aligned, lying actually in the granodiorite (Baker et al., 1939). These form a partial screen, but the granite is apparently the younger rock. The Baw Baw granodiorite is further discussed below.

The chief conclusions that can be drawn concerning the Marysville Igneous Complex are: —

1. Several of the lower flows beneath the Cerberean Volcanics in the Cerberean Cauldron originally extended beyond the cauldron as defined by the ring-dyke, and are now preserved by down-faulting in the cauldron.

2. The very thick Cerberean Volcanics and the lavas of the Acheron Cauldron were, however, extruded only with the subsiding cauldrons.

3. The mechanism of extrusion of the major flows being a consequence of cauldron collapse, a magma chamber of large dimensions, certainly

more extrusive than the area of the Marysville Complex (some 1500 sq. miles of exposed igneous rock, in an area of 2500 sq.miles) must have existed below the region.

The Devonian Dacite Suite in Victoria

It has long been known, especially through the work of SUMMERS (1923) that the Victorian occurrences of hypersthene dacite are all co-magmatic and that the associated granodiorites and adamellites are very closely allied with the hypersthene dacite in time and petrogenesis. All other work, especially that of EDWARDS (1932 a, 1932 b, 1956) has substantiated these conclusions, so that the few areas where hypersthene dacite occurs as flows of great thickness and extent (Acheron Cauldron, Dandenong Ranges, Mt. Macedon and Violet Town) were certainly part of an Upper Devonian co-magmatic region. Likewise many massifs of granodiorite and adamellite must be co-magmatic with this dacite and related differentiates. This is, for example, perfectly clear for the granodiorites of the ring dykes in the Marysville Complex; it may be taken as virtually certain too for the Baw Baw granodiorite, which is one of the many elliptical massifs of this rock in Victoria. Again in the Strathbogie Ranges, granite is associated with a lava succession that is consanguineous with the Marysville volcanic rocks as shown by WHITE (1954). Since the lavas extruded into the Cerberean cauldron include rhyolite and show a gradation to dacite, it may be further inferred that granite, adamellite and granodiorite are all to be expected among the consanguineous intrusions. SUMMERS, without the benefit of present knowledge, had already demonstrated this on petrochemical grounds. It remains to discuss the structural conditions in the various volcanic complexes and intrusions, as it is certainly to be anticipated that crustal fracturing with cauldron subsidences and major stoping may be represented in many of these Upper Devonian igneous complexes. The following brief accounts will indicate at least some working hypotheses to be tested in the field. This is particularly necessary since for some areas already mapped in detail the possibility of cauldron collapses has been overlooked. One large volcanic complex has, for instance, been conceived as a synclinal keel.

Strathbogie Complex

Some 25 miles to the north of the Cerberean Complex a large granite massif forms the Strathbogie Ranges, and near Violet Town an area of 200 sq.miles is occupied by quartz-biotite-hypersthene dacite, exactly similar to that of the Marysville Complex (Fig. 3). WHITE (1954) by detailed mapping has shown that the dacite occupies a sub-elliptical downwarp with a sharply upturned edge, in which the base of the lavas is strongly dragged up against the granite. Rhyolite occurs as a thin sheet beneath the hypersthene dacite. Along the southern contact is a discontinuous screen of Siluro-Devonian bedrock and a series of late-stage granitic differentiates. A point of special interest is the presence in the dacite of

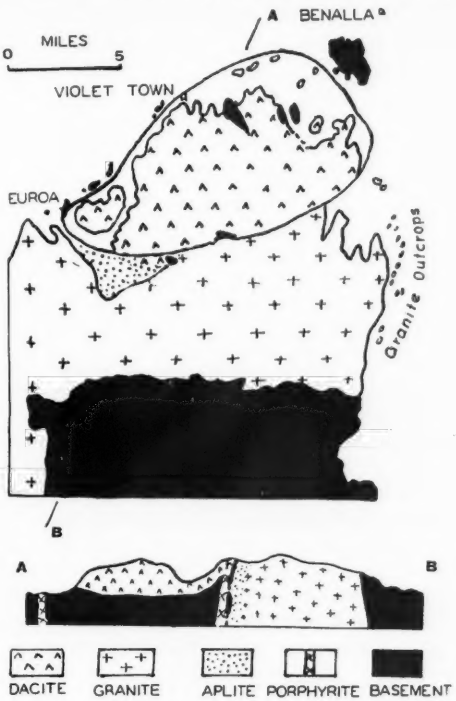

Fig. 3. The Violet Town Volcanics and the Strathbogie Granite (after White, 1954).

numerous inclusions of acid porphyry, making the rock exactly similar to the "snobite" hybrid of the Cerberean Cauldron. As White points out, the "dacites" show intrusive characteristics around the margins of the mass on the north and south, but large areas covered by alluvium on the east and west obscure the relationships there. Although he regarded the evidence as insufficient to postulate a ring-fracture, he concluded that the Strathbogie and contiguous Terrip Terrip Granites were emplaced by major stoping, and, indeed no reasonable alternatives to cauldron collapse can be presented to account for the lavas; the present author, in fact, prefers to regard intrusive "dacite" as marking the marginal dyke to the cauldron (see Fig. 3), and an intrusion of granodiorite porphyrite on the southern edge as part of this marginal zone of intrusives.

Dandenong Ranges

Following pioneer mapping by Morris Morris (1914), this area some 25 miles from Melbourne was studied by the author in demonstrating the

general structure (HILLS, 1941), and more recently it has been re-examined by EDWARDS (1956). A succession of lavas very similar to that of the Marysville Complex is present, except that the lowest flows are toscanite of a type not known elsewhere in Victoria.

Volcanic Sequence, Dandenong Ranges

6. Hypersthene dacite (Upper Dacite),
5. Quartz-biotite dacite (Middle Dacite),
4. Tuffs with plant remains,
3. Quartz-biotite dacites with almandine (Lower Dacites),
2. Rhyolite,
1b. Upper Toscanite,
1a. Lower Toscanite.

On the south the lavas are intruded along an east-west line by biotite granodiorite which metamorphoses the hypersthene dacite forming a biotite schist (SKEATS, 1910), and along the eastern margin there are small cupolas of granodiorite and porphyrite (Fig. 4). As EDWARDS remarks, "Some collapse of the roof accompanied the withdrawal of magma to form lavas, and following the major extrusion of the Upper Dacite, or contemporaneously with its extrusion, a major subsidence occurred..." A comparison is made with the Marysville cauldron subsidence.

This complex is only 10 miles from the Acheron cauldron. The plant-bearing tuffs are lithologically very like the Taggerty fish beds, and the two complexes are undoubtedly of the same age and broadly similar as to origin.

Mt. Macedon, another great massif of hypersthene dacite (SKEATS and SUMMERS, 1912), has not been re-examined structurally and its extrusion mechanism remains unknown.

Jemba Cauldron-Subsidence

In a part of north-eastern Victoria mapped by EASTON, a great mass of rhyolite forming Mount Burrowa (4181 ft.) rests on granite and Ordovician sediments. This is the Jemba Rhyolite (EDWARDS and EASTON, 1937), which except for the apparent absence of cordierite is closely similar to the nevadite of the Marysville Complex. The region includes a dyke-swarm of acid porphyries and quartz diorite, chiefly in close-knit assemblages trending N.E., but one series of quartz-porphyry dykes, much broader than the average, cuts across the N.E. dykes and forms a discontinuous arcuate line enclosing the lavas on the north and east. Both map and section are strongly suggestive of ring fracturing and cauldron subsidence (Fig. 5). It is of particular interest that several dykes of the N.E.-trending swarm are offshoots of the postulated ring-dyke, and the situation of the Jemba cauldron on one of the most intense concentrations of dykes is an indication of regional tectonic influences in the localization of the volcanic sink, as with the Tertiary ring complexes of western Scotland.

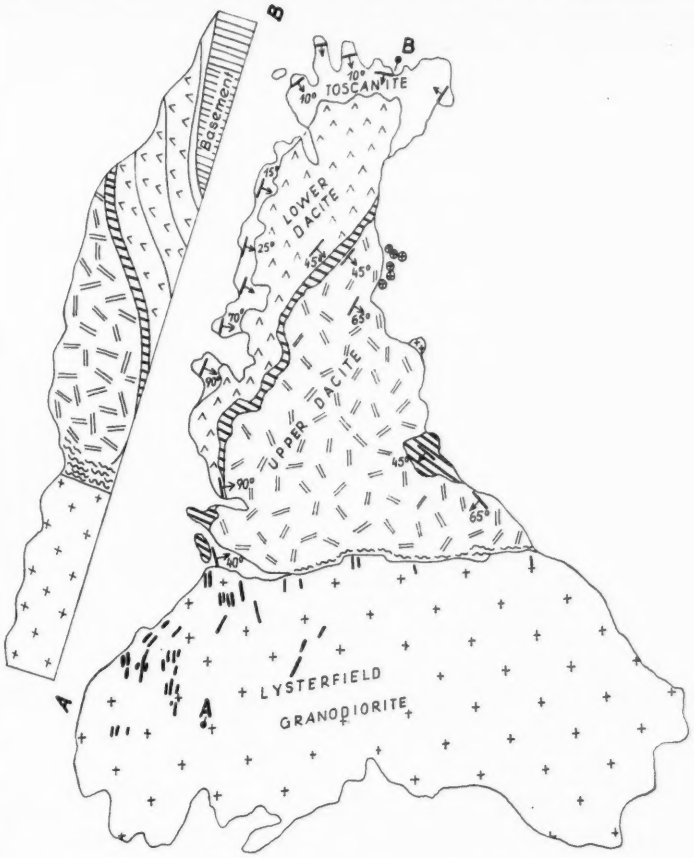

Fig. 4. The Dandenong Ranges Volcanics and Lysterfield Granodiorite. (Mapping by MORRIS, HILLS, and EDWARDS — from EDWARDS, 1956.)

Talbingo Mountain

Some 50 miles W.S.W of Canberra is a plateau attaining an elevation of 4541 ft. at Mt. Talbingo (Fig. 6), whose physiographic resemblance to the Acheron and Cerberean Cauldrons is so strong that the author, after seeing it, discussed the geology with Mr. ADAMSON of the New South Wales Department of Mines, who recently surveyed it. The map (Fig. 6) reveals a central mass of volcanic rocks and sediments, capped with rhyolite, with strong inward dips at the margins and a large acid porphyry dyke on the west, which continues as a very broad dyke further north.

Although a distinction was not made because of lack of time in the field, a large porphyry intrusion also forms much of the eastern edge of the volcanic area. Dips in the sediments, tuffs and lavas beneath the rhyolite capping are almost vertical near the margins, but flatten rapidly towards the centre, especially on the west, the structure being asymmetrical. If the occurrence is to be thought of as a synclinal keel, the folding involved would be extreme to produce the very high dips recorded, which is quite inconsistent with the regional geology and also with the fold structures of the basement rocks (Silurian and Ordovician). The structure is seen to be that of a vertical-sided basin with a flat centre. Furthermore the occur-

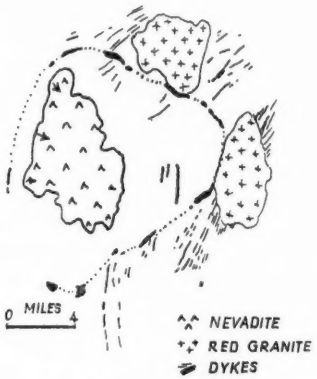

Fig. 5. Sketch of suggested Jemba Cauldron Subsidence, N.E. Victoria. (Mapping by Easton — from Edwards and Easton, 1937.)

rence of igneous rocks is isolated. There is no regional sheet of lavas to which those of Talbingo Mountain may be related. For all these reasons the hypothesis of cauldron-subsidence may most reasonably be postulated.

Granitic Plutons

The long-held tenet that many Victorian granodiorite, adamellite and granite masses are consanguineous with hypersthene dacite, rhyodacite, toscanite and rhyolite flows is very strongly justified by the recognition of cauldron subsidences, and the further tenet that these plutons are of magmatic origin is vindicated. From regional geology it is known that the intrusions closely associated with lavas are post-orogenic. The hypothesis of piecemeal, overhead magmatic stoping has been widely promulgated, and the effects of marginal assimilation demonstrated notably by the work of Tattam (1925), and Baker (1936). The postulate of stoping has been based mainly on the lack of disturbance of the strongly folded Ordovician, Silurian and Devonian sediments at granitic contacts, but the alternative

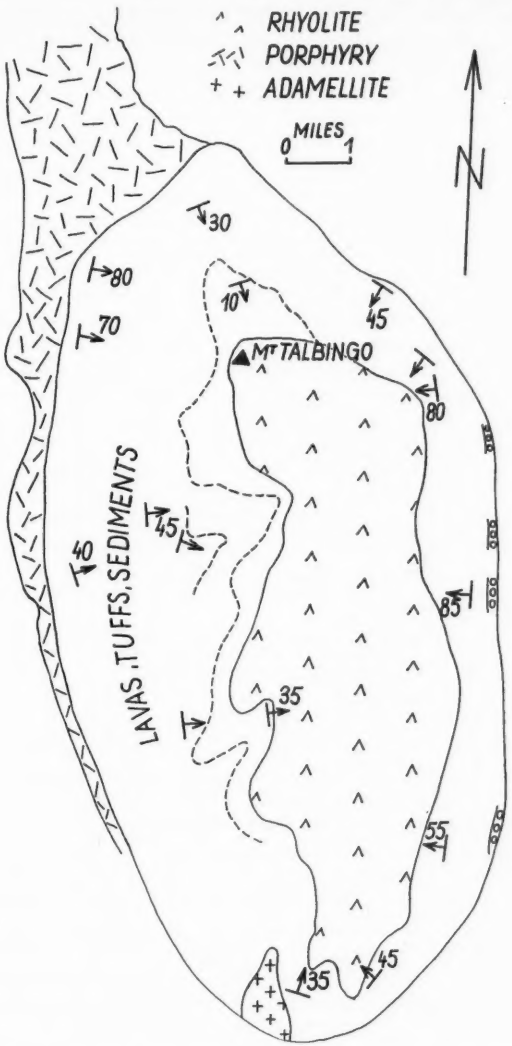

Fig. 6. Mt. Talbingo Cauldron Subsidence, N.S.W. (Simplified from an unpublished map by C. L. ADAMSON; reproduced by kind permission of Dr. F. W. BOOKER, Chief Government Geologist, N.S.W.)

hypotheses of major stoping in the sense of DALY (subterranean cauldron collapses; CLOUGH, MAUFE and BAILEY [1909]), actual fissure-filling, and diapiric injection have not been discussed. BILLINGS (1945) has pointed out that in areas of ring-tectonics, plutons of circular or elliptical outline are found and afford presumptive evidence for major stoping or some related process. This notion is clearly applicable to many Victorian examples (see Fig. 1), but since some cauldrons are polygonal rather than rounded, similar reasoning also may be applied to intrusions with straight margins. The possibility of diapirism is, naturally, not so strong for these polygonal massifs, but plug-like uplifts by magma of straight sided blocks (as well as of sub-circular) is a distinct possibility.

Fissure-filling. — The filling of a ring-fracture to form a ring-dyke has a broader significance than the immediate example of the ring-complex. It demonstrates that magmatic intrusions do fill large crustal fractures, and suggests that examples other than ring fractures may equally well exist, where the tectonic setting is favourable. The largest ring dyke recognized in Victoria is that of the Black Range Granodiorite, and it appears that this is not a single ring fault so much as an aracuate fracture along which a thin central block has subsided forming two arcuate dykes which coalesce above. The central, subsided block may be identified as the bed-rock block, enclosed by the two "horns" of the dyke at its southern end. A further variation is seen in the ring dyke around the Cerberean Cauldron, which north of Taggerty is represented by a series of en echelon dykes, and in places has very large "rafts" of bedrock included in it.

In the Canberra region of the Australian Capital Territory, granitic intrusions with some indications of internal "screens" of bedrock form large dyke-like masses parallel with a series of high angle reverse faults. NOAKES (1957) has recently analysed the relationships between the granites and faults, and concludes that a vertical stress-component must have been involved, which he attributes to the upward pressure of granite magma. His analysis shows the intimate connections between geanticlines, geosynclines and magmatism in the Lower Palaeozoic of S.E. New South Wales, and the author gratefully acknowledges the benefit of discussions on these topics. NOAKES arrives at the notion of the generation of high angle faults aided by magmatic uplift, the movement of magma up fault planes, and the widening of the intrusions by fretting, piecemeal stoping, and assimilation. Whatever may be the major structure of the plutons discussed by NOAKES and by the author, these processes are by no means subordinate and indeed appear from petrological studies to have operated at almost all intrusive contacts of granitic rocks.

Major stoping: ring and polygonal fracturing. Many of the geometrical effects of flow and fracture illustrated by H. CLOOS in Das Batholithenproblem, would be simulated equally well in granites emplaced by major stoping as by the diapiric injection which is, I think, implicit in CLOOS' writings. The dome of flow layers, the rapid disappearance of orientated flow towards the centre of a dome, the Q and L joints,

would all appear as they do in CLOOS' well-known block diagram. A radial arrangement of the jointing and dip of flow layers would, however, be seen, and the fabric of the main mass above the ring dyke would show sub-horizontal rather than vertical control of injection to have operated.

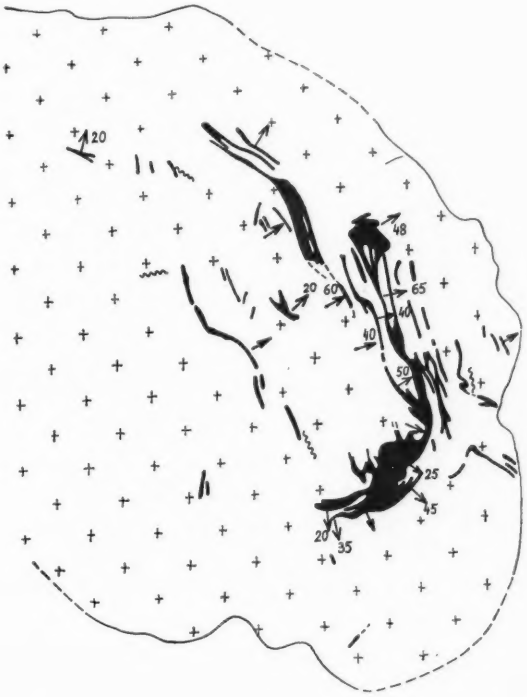

Fig. 7. The Mt. Kooyoora Granite (eastern part). (After JONES, 1955.)

Many Victorian granite stocks show a strong concentric arrangement of different petrological types, obviously in some instances not differentiates in situ but injections, which would involve such sudden aggrandisement of the magma chamber at the time of emplacement, that ring fracturing rather than "shouldering apart" seems inevitably to have been involved.

Inglewood Granite. An example mapped by SPENCER JONES (1955) is afforded at Mt. Kooyoora, near Inglewood, where microgranite, aplite and pegmatite dykes occur, firstly in a series parallel with the granite margin, and secondly in transgressive sets corresponding with major joints. The circumferential dykes dip at angles such that they form the

flanks of a dome-like structure, with decreasing dips from the margins towards the centre of the mass (Fig. 7).

The Cobaw Granite (SINGLETON, 1949) has a sharply defined marginal zone of porphyritic granite up to 2 miles wide, and an inner core of equigranular granodiorite (Fig. 8). Orthoclase phenocrysts in the granite rim are orientated (where mapped at Tooborac) in vertical flow layers parallel with the boundaries of the ring-intrusion. SINGLETON concludes

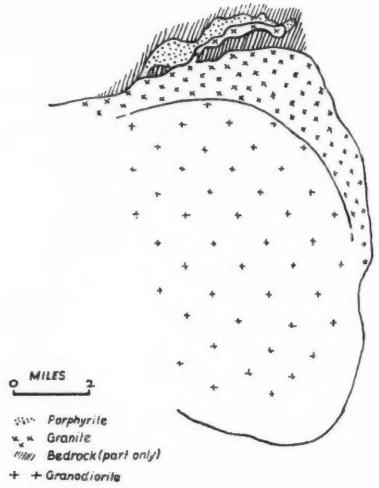

Fig. 8. The Pyalong Granodiorite at Tooborac. (After SINGLETON, 1949.)

that the granite annulus is younger than the granodiorite, and he was led to postulate ring fracturing for the Pyalong Granite, which has an arcuate eastern boundary. The Cobaw Granite as a whole is, however, markedly sub-rectangular. It is especially interesting that an arcuate dyke of hypersthene porphyrite older than and metamorphosed by the granite, follows the granite contact at Tooborac. This is the only known occurrence of an intrusive hypersthene-bearing rock related to the Victorian dacites and granodiorites; the nearest occurrence of hypersthene dacite is at Mt. Macedon, 24 miles away.

The Harcourt Granodiorite is an elliptical massif joining on the N.W. with rounded intrusives south of Bendigo and at Maldon. Apart from the mountainous western edge, exposures are extremely poor and the country is largely grassland, but a remarkable physiographic effect clearly indicates some concentric structure parallel with the margin. This is shown by the course of major streams, the Coliban River and trebutary creeks,

which flow about a mile within the granite and parallel with the margin (Fig. 9).

Polygonal Intrusions. Various granite masses showing polygonal outlines have been mentioned (see Fig. 3). In the pattern of their margins, certain trends are predominant, especially the E-W, NNW-SSE and N-S, as may be seen on the map (Fig. 1). Two alternatives may be considered, on the one hand of major stoping and on the other intrusion

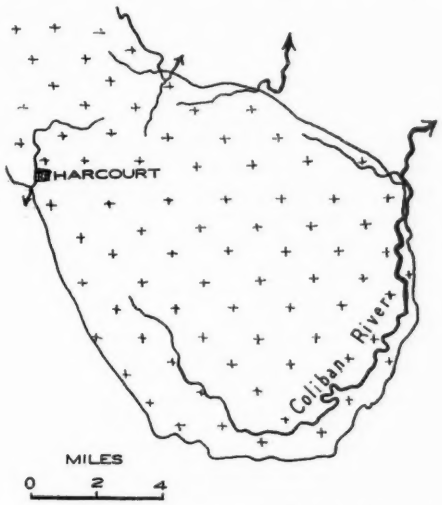

Fig. 9. The Harcourt Granodiorite, showing physiographic expression of ring structure.

by forceful uplift of large fault blocks. The two effects could, also, be combined. One reason for assuming block uplift is that in so many localities, granite or granodiorite is now found at an elevation higher than the base of the associated lavas into which they are intrusive (see, e.g., Dandenongs, Warburton, Strathbogies-Violet Town). It is, probably, the notion that granitic rocks require a cover of the order of a few thousand feet for their crystallization with granitic texture, that influences one to adhere to major stoping rather than to block uplift, but it is abundantly clear that many Victorian granodiorites with typical granitic texture crystallized at a depth of no more than 3000 ft. as shown by their intrusion into lavas of their own generation.

Petrogenesis and Magma Genesis

The petrology of the lavas of the hypersthene dacite suite demonstrates that extrusion occurred from great magma chambers in which differentia-

tion had produced a vertical gradation with rhyolite above and dacite beneath, this being reflected in the gradational relationships between lavas and in their order of superposition (HILLS, 1931; EDWARDS, 1956). The parent magma was very fluid, free from xenoliths of all kinds, and was crystallizing intratellurically when extrusion occurred. As this magma was distributed without any change in its petrochemical characteristics over an area of at least 10,000 sq.miles, and as it was present in such volumes that cauldron collapse was common, the way in which it attained its position beneath the region poses many problems, in which both geochemical and tectonic considerations must be linked. The notion that this magma was generated elsewhere and was injected beneath the region, possibly from the active zone in the east, has many points in its favour. The postulate of a forceful lateral movement of magma from the east would also satisfy the requirements for the close association of high angle reverse faults and granitic intrusions in the Canberra region, but the date of these intrusions is much earlier (Ordovician, Silurian vs. Upper Devonian) and it is not desired to discuss the broader problems of the region. However, the late Middle Devonian lamprophyric dykes of Victoria must be included in the synthesis as they occur in the same region as the dacites and are only a little older. The parent magma for these was, it is thought, acid-intermediate in composition very similar to that of the hypersthene dacite-granodiorite suite, but rich in mineralizers whereas the hypersthene dacite magma was extremely dry. It is tempting to regard these dykes as the fore-runners of an advancing wedge of magma moving from the east or north-east, the crust splitting as the magma advanced and releasing mobile lamprophyric magma with its mineralizers, during an extremely short time-interval. The dykes are flash-injections which intruded through thousands of feet of older rocks and have been mined without change for over a mile from the present surface. It has been shown (HILLS, 1952) that orogenic forces continued to operate to a small extent after the dyke injections. This in turn suggests that the presumed lateral spread of magma towards the west was at first synorogenic, but by Upper Devonian times the orogenic stresses appear to have been largely dissipated, permitting cauldron collapses into a magma body that had only a little "uplift" pressure remaining in it. The Upper Devonian and Lower Carboniferous then mark the end of all acid-intermediate igneous action in Victoria.

References

BAKER, G., 1936: The Petrology of the You Yangs Granite — A study in Contamination. Proc. Roy. Soc. Vic., vol. 48, pp. 124—158. – et al., 1939: Granite and Granodiorite at Powelltown, Victoria, and their Relationships. Proc. Roy. Soc. Vic., vol. 51, pp. 31—44. — BENSON, W. N., 1913—1915: The Geology and Petrology of the Great Serpentine Belt of New South Wales. Proc. Linn. Soc. N.S.W., vol. 37—40. — BILLINGS, M. P., 1945: Mechanics of Igneous Intrusion in New Hampshire. Daly Volume, Amer. Journ. Sci., vol. 243 A, pp. 40—68. — BROWNE, W. R., 1933: Post-Palaeozoic Igneous Activity in New South Wales. Journ. Roy. Soc. N.S.W., vol. 67, p. 9. — CLOUGH, C. T., H. B. MAUFE, and E. B.

BAILEY, 1909: The Cauldronsubsidence of Glen Coe, and the associated igneous Phenomena. Quart. Journ. Geol. Soc. Lond., vol. 65, pp. 611—678. — DAVID, T. W. E. (ed. BROWNE), 1950: Geology of the Commonwealth of Australia. 3 vols., London (Arnold). — EDWARDS, A. B., 1938: The Tertiary Volcanic Rocks of Central Victoria. Quart. Journ. Geol. Soc. Lond., vol. 94, pp. 243—318. – 1932 a: The Geology and Petrology of the Black Spur Area (Healesville). Proc. Roy. Soc. Vic., vol. 44, pp. 49—76. – 1932 b: The Geology and Petrology of the Warburton Area, Victoria. Proc. Roy. Soc. Vic., vol. 44, pp. 163—181. – 1956: The Rhyolite-Dacite-Granodiorite Association of the Dandenong Ranges. Proc. Roy. Soc. Vic., vol. 68, pp. 111—149. – and J. G. EASTON, 1937: The Igneous Rocks of North-Eastern Victoria. Proc. Roy. Soc. Vic., vol. 50, pp. 69—96. — HILLS, E. S., 1931: The Upper Devonian Fishes of Victoria, Australia. Geol. Mag., vol. 68, pp. 206—231. – 1932: The Geology of Marysville, Victoria. Geol. Mag., vol. 69, pp. 145—166. – 1941: Note on the Occurrence of Fossiliferous Tuffs in the Dandenong Ranges. Proc. Roy. Soc. Vic., vol. 53, pp. 415—422. – 1952: The Woods Points Dyke Swarm, Victoria. Sir Douglas Mawson Anniversary Volume, Univ. of Adelaide, pp. 87—100. — JONES, D. SPENCER, 1955: Radioactive Deposit near Mount Kooyoora, Inglewood. Mining & Geol. Journ. (Dept. of Mines, Vic.), vol. 5. pp. 24—32. — JUNNER, N. R., 1915: The Petrology of the Igneous Rocks near Healesville and Narbethong. Proc. Roy. Soc. Vic., vol. 27, pp. 261—285. – 1920: The Geology and Ore Deposits of the Walhalla — Woods Point Auriferous Belt. Proc. Aust. Inst. Min. Met., N.S. no. 39, pp. 127—258. — MORRIS, M., 1914, Geology and Petrology of the District between Lilydale and Mt. Dandenong. Proc. Roy. Soc. Vic., vol. 26, pp. 331—364. — NOAKES, L., 1957: The Significance of High Angle Reverse Faults in the Canberra Region. Aust. & N.Z. Assoc. Adv. Sci., Dunedin, 1957 (abstract only). — SINGLETON, O. P., 1949: The Geology and Petrology of the Tooborac District, Victoria. Proc. Roy. Soc. Vic., vol. 61, pp. 75—104. — SKEATS, E. W., 1908: On the Evidence of Origin, Age and Alteration of the Rocks near Heathcote, Victoria. Proc. Roy. Soc. Vic., vol. 21, pp. 302—348. – 1910: Gneisses and Dacites of the Dandenong District. Quart. Journ. Geol. Soc., Lond., vol. 66, pp. 450—469. – and H. SUMMERS, 1912: The Geology and Petrology of the Macedon District. Geol. Surv. Vic., Bull. No. 24. — SUMMERS, H. S., 1914: On the Origin and Relationship of Some Victorian Igneous Rocks. Proc. Roy. Soc. Vic., vol. 26, pp. 256—297. — TATTAM, C. M., 1925: Contact Metamorphism in the Bulla Area ... Proc. Roy. Soc. Vic., vol. 37, pp. 230—247. — THOMAS, D. E., 1947: The Geology of the Eildon Dam Project. Geol. Surv. Vic., Memoir No. 16. — WHITE, D. A., 1954: The Geology of the Strathbogie Igneous Complex, Victoria. Proc. Roy. Soc. Vic., vol. 66, pp. 25—52.

AUSTRALIA AND GONDWANALAND*)

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Abstract

Along the western margin of the Australian continent there exist four major sedimentary basins, filled with predominantly marine rocks from Cambrian to Tertiary in age, and up to 40,000 feet thick. Seaward these basins continue into depressions recognizable in the continental shelf and even the continental slope. Their very presence, the nature of their sediments and the composition and relationships of their fossil faunas indicate the existence of an open ocean to the west of Australia since early Paleozoic time. Composition of the Australian fossil land vertebrate faunas suggests isolation of the Australian continent since at least Permian time.

Introduction

Researches during the past 20 years have greatly altered our picture of the geological history of the western margin of Australia. It is not yet generally understood that these new results have an almost revolutionary effect on paleogeographic interpretations that are connected with the hypothetical concept of Gondwanaland as it developed during the last three-quarters of a century. It is, therefore, proposed to summarize these developments in a concise manner and to apply them to an interpretation of the relationships between Australia and the oceanic and land areas further west. The picture that will emerge is one of Australia as a very old continent, both in the geologic and in the geographic sense. Its geological structure and paleogeographic history would have been very different, if broad land connections to the west, as envisaged by many geologists, had ever existed.

History of the Gondwanaland concept

It is first necessary briefly to reconsider the main steps in the development of the ideas on the paleographic position of Australia throughout the geologic past. Essentially such a review will be one of the history of the idea of Gondwanaland, with special emphasis on its eastern half (TEICHERT, 1952 a).

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The story of Gondwanaland may be said to date back to 1875 [1]) when H. F. BLANFORD pointed out, for the first time, the facts of the distribution of the *Glossopteris* flora in India, South Africa and Australia and proposed to explain these by assuming the existence of an Indo-Oceanic Continent from Early Permian time to the end of the Miocene.

The new hypothesis gained support from NEUMAYR (1887) who accepted BLANFORD's interpretation without essential changes, also emphasizing similarities in the geologic structure and history of parts of South America and Africa and postulating the existence of a "Brasilianisch-äthiopischer Kontinent" for much of Mesozoic time.

A complete synthesis of these new ideas was given by EDUARD SUESS in his "Antlitz der Erde", where the matter was first raised in 1885, when the second part of the first volume appeared. It was here that SUESS proposed the name "Gondwana-Land" for a land mass comprising Africa, Madagascar, and the Indian Peninsula. In volume II, published in 1888, we find Gondwana-Land extended to include Australia, and in the second part of volume III, published in 1909, we read that it comprises "South America from the Andes to the east coast between the Orinoco and Cape Corrientes, the Falkland Islands, Africa from the southern offshoots of the Great Atlas to the Cape Mountains, also Syria, Arabia, Madagascar, the Indian peninsula and Ceylon". Here, SUESS followed W. T. BLANFORD who had been greatly impressed by KURTZ's discovery of the Gondwana flora in South America and in a paper in 1896 had proposed to extend Gondwana-Land westwards and southward to South America and the Antarctic Continent.

HAUG, in his classical paper on geosynclines published in 1900, did not use SUESS' term Gondwana-Land, although he strongly advocated the same idea. NEUMAYR's "Brasilianisch-äthiopischer Kontinent", renamed "Continent africano-brésilien", was believed to have existed until the Cretaceous period, but to have been smaller in the Paleozoic. On the other hand there existed the "Continent australo-indo-malgache" and the two were united until the Jurassic period when the Strait of Mozambique came into existence.

The Gondwanaland idea became more deeply rooted in geological thought when it appeared on maps in well-known treatises such as FRECH's "Lethaea" (1902) and HAUG's "Traité" (1911). FRECH drew paleogeographic maps for the Carboniferous on which an "Indoafrikanischer Continent" includes Australia (separated from a doubtfully included Sundaland area and the Philippines), the Indian Ocean, Peninsular India, most of Africa, the South Atlantic and most of South America. No map for the Permian period is given but from statements in the text (p. 622) it seems that the continent is supposed to have been of very much the same size

[1]) To the writer it has always seemed an intriguing coincidence that the Gondwanaland concept was born exactly one hundred years after Captain James Cook had returned (in 1775) from his second voyage around the world. It was on this voyage that the age-old geographical phantasies of a Terra Australis were finally disproved.

during that period. Maps for the Silurian and Devonian periods show a continental area restricted to Africa, India (including Burma and Indochina), the East Indies, New Guinea and Australia.

HAUG, in his "Traité" presented a series of paleogeographic maps representing graphically ideas similar to those published by him in 1900. He accepted SUESS' Gondwana-Land in its widest sense for the Anthracolitic period (Carboniferous and Permian). During the Jurassic period this continent broke up into two as already described by him in 1900. He also projects Gondwanaland back in time and maps for the Silurian (including Ordovician) and Devonian periods show a "continent équatorial" with outlines very similar to those of the later Gondwanaland.

After all, what was more reasonable than to assume that such a huge continent could not have come into existence suddenly in the Carboniferous and Permian periods? If there was evidence for its existence in the late Paleozoic, it was logical to suggest that it had been there before. Thus, in 1907, ARLDT had hinted that Gondwanaland may have existed in Precambrian time.

Such ideas seemed to receive further support from studies by RUEDEMANN (1922) on the distribution of folds and trend lines in the Precambrian shields of the southern hemisphere. These, he believed, showed a general N.—S. alignment in Africa, India and Australia and RUEDEMANN concluded that an "A r c h i - G o n d w a n a" had come into existence in Precambrian time, extending from eastern South America eastward to Middle Australia and the East Indies — "the evident ancestor of the Great Gondwanaland". In a series of paleogeographic maps Gondwanaland is shown to have had its greatest extent in the Upper Carboniferous when it included all of South America, almost all of Africa, all of Arabia, peninsular India, Australia and New Zealand, as well as the intervening oceanic areas. In the writings of J. M. CLARKE (1919) and of ABENDANON (1919), this southern land had assumed even greater proportions.

By the 1920's the Gondwanaland idea had become deeply rooted and generally accepted in textbooks and treatises. Thus, KRENKEL in his "Geologie Afrikas" (1925) stated: "Das Dasein einer ausgedehnten Gondwana bis an die Karbon-Perm-Grenze ist sicher." FOX (1931) stated: "From the evidence brought forward it appears to be practically certain that a vast continental area, relatively permanent in the Upper Paleozoic and Lower Mesozoic era, existed in the southern hemisphere and included what are now parts of India, South Africa, South America, Australia, and Antarctica." The final break-up of this continent according to Fox, occurred with the eruption of the Deccan lavas at the close of the Cretaceous period.

It is well known that the Gondwanaland hypothesis played a considerable role in the development of the ideas on continental drift. Thus Gondwanaland forms part of WEGENER's original P a n g a e a. Until the last (4th German) edition of his well-known book, published in 1929, WEGENER believed that the southern continents (with peninsular India) formed one single land mass which began to break up in the east (Indian Ocean)

during the Jurassic period. Reassembly of the continental fragments in a manner different from WEGENER was suggested by ARGAND, by SALOMON-CALVI, by DU TOIT, and others, without critical reappraisal of the paleogeographic facts in the Australian sector.

During the 1920's Gondwanaland rose to considerable importance in several geotectonic syntheses, notably those of STILLE (1924) and of STAUB (1925). Following SUESS, it was generally imagined that the Tertiary folded belt from the Mediterranean to East Asia owed its origin to a counter movement of a large northern block ("Laurasia" of STILLE) and a southern block (Gondwanaland). Between these two the alpine geosyncline had been squeezed out as between the two jaws of a gigantic vise. STAUB projected this picture back to earlier periods and explained the folding of the Paleozoic era by similar movements.

Dissenting voices had not been missing altogether as some disturbing facts were gradually gaining recognition. From the west coast of the Australian continent the first marine fossils of late Paleozoic age had been described as early as 1883, from what became known later as the North-West Basin (now Carnarvon Basin) (HUDDLESTON 1883). Progress in knowledge of these faunas was slow indeed. ETHERIDGE described the first small late Paleozoic marine fauna (identified as Carboniferous, now recognized as Permian) from the Desert Basin (now Canning Basin) in 1889. In 1890 followed papers by FOORD and others in the Geological Magazine. But it was not until A. GIBB MAITLAND explored the Irwin River and Carnarvon Basins and brought home more representative collections that the importance of the marine upper Paleozoic and its faunas in Western Australia began to be recognized. The newly available material was described by ETHERIDGE in a number of important papers between 1903 and 1918 and the new facts were fully summarized by GIBB MAITLAND in 1919. If this work had received the general recognition it deserved we would have been spared many ill-founded paleographic speculations in later years.

As early as 1907 KOKEN had pointed out the presence of marine rocks of Permian age along the west coast of Australia and made the important observation that any land connection which might have existed between India and Australia must have ceased at the end of the main glacial period in Early Permian time. On the whole he rejected the idea of a huge southern continent as shown on FRECH's maps.

SCHUCHERT gave much attention to Gondwana paleogeography, and none of the maps published by him at various times (1916, 1929, 1932) show more than narrow land bridges connecting the southern continents. This was also the basic concept of BAILEY WILLIS (1932).

RAGGATT (1936) and TEICHERT (1941) demonstrated the existence of unexpectedly thick marine Permian sequences in the sedimentary basins of Western Australia. FOURMARIER (1937, 1940) called attention to BESAIRIE's discoveries of marine rocks of Permian and Triassic age in Madagascar and concluded that the history of the western part of the Indian Ocean dates back to Permian time and that, therefore, permanence of the Indian Ocean since the late Paleozoic had to be assumed.

STILLE, in 1944, reviewed the history of Gondwanaland and, taking cognizance of some of these new facts, came to the conclusion that its break-up in the Indian Ocean area took place as early as Permian time. FAIRBRIDGE (1948) arrived independently at the same conclusion and similar statements may be found in even more recent publications (e.g. BEURLEN, 1954). Thus, the story of Gondwanaland had turned a full circle: the break-up was now postulated for the time when, according to the original theory, the continent was supposed to have begun its existence. The late Paleozoic which once seemed to have furnished evidence for the beginning of Gondwanaland, now gave proof of its destruction.

Principal geologic features of the western continental margin of Australia

In every discussion about Gondwanaland Western Australia must play a key role, because its geology has probably been more thoroughly revolutionized than that of any other part of the southern hemisphere (with the possible exception of Brazil), since the Gondwanaland hypothesis was proposed. As has already been pointed out, if even the few facts on the distribution of marine faunas known 50 and 60 years ago had received deserved attention, much unnecessary and ill-founded speculation could have been avoided.

In the following we shall focus our attention on a strip of land up to 200 miles wide from the present west-coast. East of this strip lies the great Australian shield which in some places projects to the present coast and which locally is also covered with younger sediments most of which we may disregard in this inquiry.

In this coastal strip we find four major areas of significant accumulations of marine sediments, separated by three projections of the Australian shield. The sedimentary areas are customarily referred to as "basins" although they are not structurally closed depressions. The two largest were for about half a century known as Desert and Northwest Basins, but have lately been renamed Canning and Carnarvon Basins respectively. An embayment of the third and northernmost basin was first named Burt Range Basin by MATHESON and TEICHERT (1948); it turned out to form part of a much larger area of sedimentation which is now known as Bonaparte Gulf Basin (REEVES, 1951). Immediately to the south of it is a smaller, and older basin, the Ord Basin, with volcanics and marine sediments of Cambrian age. Along the southern portion of the west coast lies a narrow basin, called the Perth Basin, and in the southeastern portion of Western Australia there is a sixth basin, the Eucla Basin, with little more than 2,000 feet of Mesozoic and Tertiary sediments. The Ord and Eucla Basins will not be considered in detail in this paper. All basins have been renamed in recent years (see GENTILLI and FAIRBRIDGE, 1951). In order to preserve continuity both old and new names are given below. The stratigraphic sections will only be described in most general terms, indicating mainly the relative thicknesses of marine and nonmarine rocks.

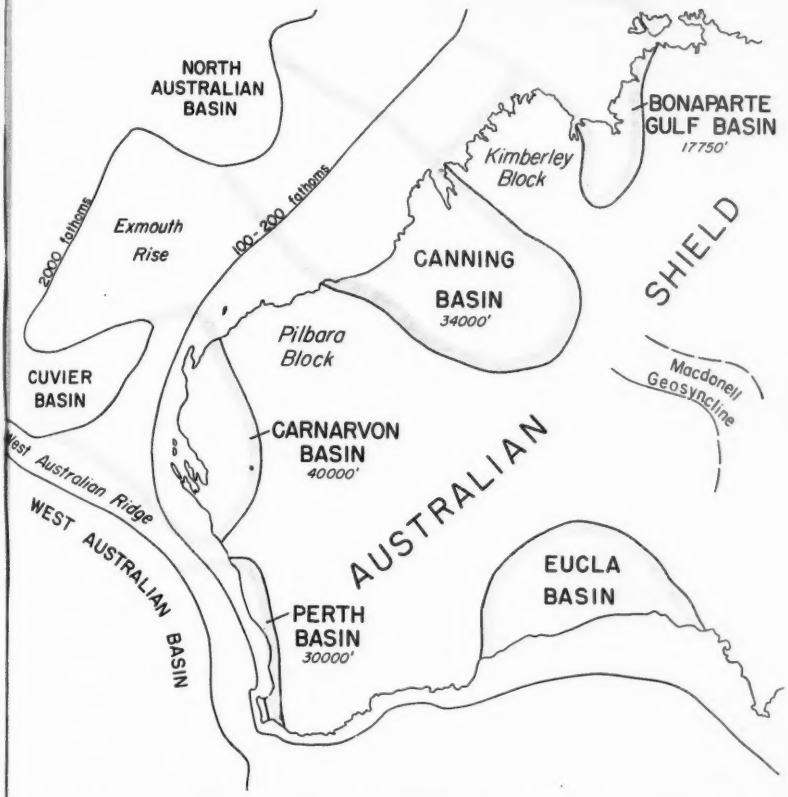

Fig. 1. Map of Western Australia und adjoining parts of Indian Ocean showing main structural features of continent and ocean floor. Figures below names of major basins indicate maximum thicknesses of sedimentary rocks in feet. Scale of this and following maps is about 1 : 25,000,000.

1. Sedimentary Basins (See Fig. 1)

a) Bonaparte Gulf Basin (= Gulf Basin of earlier authors; includes Burt Range Basin, MATHESON and TEICHERT, 1948), situated in the southern extension of Joseph Bonaparte Gulf, at the southeastern edge of the Timor Sea. The presently exposed part of the basin occupies somewhat more than 6,000 square miles, but as observed by FAIRBRIDGE (1951) and by NOAKES et al. (1952) Joseph Bonaparte Gulf itself must be regarded structurally as a continuation of the basin and the shelf here most certainly is underlain by sedimentary rocks of Paleozoic and Mesozoic age.

The greater part of the stratigraphic section of the Bonaparte Gulf Basin was first described by MATHESON and TEICHERT (1948). The basin was renamed by REEVES (1951) and its stratigraphy described in more detail by NOAKES, ÖPIK, and CRESPIN (1952) and by TRAVES (1955).

The generalized section is as follows:

System	Thickness in feet
Upper Jurassic to Lower Cretaceous	up to 100
Permian	1,500—2,000
Carboniferous	4,150
Devonian	7,000
Ordovician	500 +
Cambrian	approx. 4,000
Total	17,750

The sequence begins with marine rocks of Early Cambrian age, continuing into rocks of Middle and Upper Cambrian age (TEICHERT, 1950), but much of the section has not yet been studied in detail. The Ordovician rocks are marine (glauconite sandstones), as are most of the rocks of Devonian and Carboniferous age. The latter correspond in part to rocks of the lower part of the Mississippian of the United States but also include some Upper Carboniferous rocks. The Permian rocks, mostly of Sakmarian and Artinskian age, are generally marine, except at the southernmost edge of the Basin. The rocks of Cretaceous age are marine and richly fossiliferous.

b) Canning Basin (= Desert Basin of earlier authors; includes Fitzroy Basin of BRUNNSCHWEILER). This is an area of about 170,000 square miles of sedimentary rocks. Long known as Desert Basin this large feature was renamed Canning Basin by GENTILLI and FAIRBRIDGE (1951). However, BRUNNSCHWEILER (1954) restricted this name to the larger southwestern part of the basin (with mainly Mesozoic strata) and called the northeastern (mainly Paleozoic) part Fitzroy Basin.

The following systems are represented in the Canning Basin:

System		Thickness in feet
Cretaceous (Lower)		up to 470
Jurassic (Middle? to Upper)		about 1,000
Triassic (Upper)		up to 1,100
Permian		15,600
Carboniferous	Upper	5,000 +
	Lower	1,400
Devonian (Middle and Upper)		up to 7,500
Ordovician (Lower and Middle)		2,630 +
Total		approx. 35,000 +

This stratigraphic section is a composite one, based on information published by TEICHERT (1947, 1949 b), GUPPY and ÖPIK (1950), GUPPY et al. (1952, 1958), BRUNNSCHWEILER (1954), and on personal communications by GLENISTER. It is quite possible, even probable, that nowhere in this huge area were all these rocks ever deposited in complete sequence. Even so, this composite section reflects the fact that parts of this basin were a major negative element throughout geologic times.

The Ordovician, Devonian and Carboniferous rocks are marine, the Permian rocks about half marine, half lagoonal, estuarine, or fresh-water in origin, including basal glacial and aqueo-glacial rocks. The Triassic rocks are of lagoonal to fresh-water facies, the Jurassic and Cretaceous mostly marine.

c) Carnarvon Basin (= Northwest Basin, MAITLAND, 1901). This basin covers an area of about 45,000 square miles and is filled with marine sediments from Devonian to Tertiary in age. The section according to TEICHERT (1949 a, 1952 b), CONDON (1954, 1956), and MCWHAE et al. (ms.) is as follows:

System	Thickness in feet
Pleistocene	up to 500
Tertiary (Paleocene to Pliocene)	up to 2,500
Cretaceous (Lower and Upper)	up to 2,200
Jurassic	11,460
Permian (mostly Lower and Middle)	up to 13,000
Carboniferous (Mississippian)	up to 2,600
Devonian (Middle and Upper)	4,900
Silurian (Lower? and Middle)	about 3,000
Total	up to about 40,000

The Devonian sequence is predominantly marine, the Carboniferous part marine, part lacustrine. The remainder of the section from Lower Permian to Pliocene is, with insignificant exceptions, wholly marine. Again there are probably few, if any, places where the entire section is present. The older rocks are now found farthest inland and the history of the basin is undoubtedly one of progressive westward movement of the shoreline, or rather: successive transgressions generally advanced for decreasingly shorter distances inland from at least 200 miles during the Devonian and Carboniferous periods to not more than 20 or 30 miles in the Pliocene. The basin is complex structurally. The Devonian and Carboniferous rocks are strongly faulted along the eastern margin. The Permian belt is also faulted, mostly antithetically, during uplift of the West Australian shield after the Permian period (TEICHERT, 1952 b, 1957). But near the present coast, at Carnarvon, Mesozoic rocks seem to rest disconformably on Devonian (or Silurian) rocks (THOMAS and DICKINS, 1954), thus confirming possibilities of a Permian "borderland" in this vicinity, first suggested by the writer in 1947 (p. 68).

d) Perth Basin. The nomenclature of this sedimentary area is still in a state of flux. It corresponds to the Perth and Greenough Regions of E. DE C. CLARKE (1926), the Southwest Coastal Basin of TEICHERT (1947), the major part of the 'Swan Coastal Belt" of GENTILLI and FAIRBRIDGE (1951), including the Irwin Basin of Paleozoic age of CLARKE, PRENDERGAST, TEICHERT and FAIRBRIDGE (1951), the Swan Basin of CARRIGY and FAIRBRIDGE (1955), and the Perth Basin of CONDON (1956). The latter name is here adopted. The basin is now under study by J. R. H. MCWHAE and collaborators.

Although the total stratigraphical column in this basin is now known to be very thick, details of the succession are as yet very incompletely known and it is better not to present a formal stratigraphical table. In the northern part of the basin about 30,000 feet of unfossiliferous sediments underlie the basal Permian beds. In the Moora district further south a thinner sequence contains algal material and problematical biostromes. CONDON (1956 b) has announced fossils of possibly Ordovician age from this series, but identifications are in dispute and all that can be said now (GLENISTER, personal communication) is that these beds belong to the Early Paleozoic or Late Proterozoic era.

The Permian is well known from the Irwin River area in the northern part of the basin (CLARKE, PRENDERGAST, TEICHERT and FAIRBRIDGE, 1951). It is now known to be over 5000 feet thick. This section is of particular interest because in it the early Permian ammonoid genera *Metalegoceras* and *Uraloceras* (TEICHERT & GLENISTER, 1952) occur stratigraphically well below plant beds which contain the well known *Glossopteris* flora (including *Gangamopteris* and *Vertebraria*) in association with genera of northern affinities such as *Phyllotheca, Sphenophyllum, Sphenopteris, Cladophlebis,* and *Bothrodendron.*

The Triassic system is represented possibly by over 1,000 feet of marine beds which underlie the Jurassic in the Geraldton district, but may range down into the Upper Permian. Jurassic, both marine and continental, is present with a possible thickness of as much as 6,000 feet. In the southern part of the basin there are sandstones of Jurassic to Cretaceous age (BALME, 1957), and marine Upper Cretacaeous in the center of the basin reaches 500 feet. Tertiary sandstones and shale may attain 1,000 feet or more. According to seismic studies by THYER and EVERINGHAM there should be as much as 30,000 feet of sediments in the central part of the basin, but the exact stratigraphic sequence remains yet to be worked out.

2. The Precambrian Blocks

The Precambrian blocks separating the sedimentary basins discussed above are projections of the great Australian shield. They need not be discussed in detail.

The Bonaparte Gulf and the Canning Basin are separated by the Kimberley Block. Between the Canning Basin and the Carnarvon Basin lies the Pilbara Block. In both these blocks the older Precambrian basement is covered by extensive and thick sedimentary deposits of the Nullagine

series of younger Precambrian age. It is possible that some rocks now included in this series are Cambrian in age (TEICHERT, 1947, p. 7), but the evidence on hand is very meagre. Apart from this there is no indication that these blocks were ever covered by seas of Paleozoic or later age.

Between the Carnarvon and Perth Basins, there is a small block of Precambrian rocks, the Greenough Block of GENTILLI and FAIRBRIDGE. It may well be that during the late Paleozoic and in Mesozoic time these two basins constituted one more or less continuous sedimentation area.

The Perth Basin continues southward between the small coastal Naturaliste Block and the main mass of the Australian shield until it strikes out into the Southern Ocean. There is evidence of lacustrine deposition during Permian time in some places on the shield itself, close to its western margin (FAIRBRIDGE, 1952).

Features of the Western Australian Continental Shelf

Very interesting analyses of the Western Australian continental shelves have been published by FAIRBRIDGE (1953) and by CARRIGY and FAIRBRIDGE (1955). They have shown that by and large the features of the shelf closely parallel those of the adjacent mainland.

Negative areas (basins) in the mainland belt correspond to depressions in the shelf, positive areas (blocks) to swells or rises on the shelf. The only exception is the Browse Depression of the Sahul Shelf which, framed by two rises, lies off the North Kimberley Block.

The features of the mainland and of the continental shelf may be contrasted as follows (positive areas in italics):

Mainland	Continental Shelf
Bonaparte Gulf Basin	Bonaparte Depression
	Londonderry Rise
North Kimberley Block	Browse Depression
	Leveque Rise
Canning Basin	Rowley Depression
Pilbara Block	*Dampier Rise*
Carnarvon Basin	Dirk Hartog Shelf
Greenough Block	*Albrolhos Rise*
Perth Basin	Rottnest Shelf

It is reasonable to assume that the geotectonic elements of the shelf and the adjacent mainland are continuous. Its physiographic features seem to portray a geologic history which is essentially similar to that of the mainland margin. The west Australian continental shelf, thus, is not a comparatively recent feature as is claimed for the shelves of some other continents. Since the early Paleozoic it was part of the Australian continental mass whose geologic history it has shared.

Stratigraphic and Paleogeographic Summary
(See Figs. 2—7)

In the following a brief review will be given of the significant features of the geological systems as developed in the various Western Australian basins. The main emphasis will be placed on faunistic relationships.

The only datable rocks of Cambrian age are found in the Bonaparte Gulf Basin and in the Ord Basin immediately south of it. Indications of a wider distribution of Cambrian rocks over parts of the Precambrian shield (TEICHERT, 1947) are in need of further verification.

Faunistically the Cambrian of the Bonaparte Gulf and Ord Basins through its trilobites is intimately related to Asia (TRAVES, 1955, 1956, ÖPIK, 1956). The earliest faunas belong to the *Redlichia* province (MATHESON and TEICHERT, 1948) which ÖPIK now regards as earliest Middle Cambrian. These are followed by Middle Cambrian faunas with *Solenoparia* (TEICHERT, 1950), *Damesella* and *Blackwelderia*. The latest fauna contains *Crepicephalus* or a closely related genus and is of early Upper Cambrian age.

Undoubted Ordovician (Fig. 2) is known from the Bonaparte Gulf and Canning Basins. In the former it is represented by glauconitic sandstones (Pander greensand) with *Lingulella* and the conodonts *Drepanodus* and *Acontiodus* (TRAVES, 1955) of Lower Ordovician (Tremadoc) age. In the Canning Basin the Ordovician is represented by richly fossiliferous limestones (GUPPY and ÖPIK, 1950) from which a varied fauna of Middle and Upper Canadian cephalopods has been described (TEICHERT and GLENISTER, 1954). This fauna is characterized essentially by Ellesmeroceratida, Tarphyceratida and early Endoceratida of predominantly North American affinities. Ordovician outcrops are restricted to a small locality near 250 miles inland from the Indian Ocean, but Ordovician rocks have recently also been penetrated by a deep bore near the coast at Dampier Downs (MCWHAE et al., ms.). Ordovician rocks may occur in the Perth Basin, though this has to be verified and their affinities cannot be stated.

Until recently rocks of Silurian (Fig. 2) age were unknown in Western Australia. However, in 1957 Middle, and possibly Lower Silurian beds, identified by conodonts, nautiloids, and brachiopods were penetrated by a bore in the Carnarvon Basin (GLENISTER, personal communication). The paleogeographic relationships of these beds cannot yet be stated.

Rocks of Devonian age (Fig. 3) are known in considerable thickness from all major basins except the Perth Basin. Lithological as well as paleontologic facies offer a complex picture which cannot be discussed in detail here. In the Canning Basin (TEICHERT, 1943, 1949) the Middle Devonian sedimentation is initiated with a bed crowded with *Stringocephalus* (GLENISTER, personal communication). This is followed by a great thickness of *Amphipora* limestone overlain by brachiopod limestones (MCWHAE et al., ms.). The associated faunas are rich and of cosmopolitan character. They include *Receptaculites* and *Sphaerospongia* (HOWELL, 1957), the

brachiopod genera *Leptaena, Rhipidomella, Schizophoria, Productella,* many spiriferids, *Atrypa, Gypidula, Camarotoechia, Leiorhynchus, Uncinulus, Hypothyridina, Pugnax,* and others, the pelecypods *Paracyclas antiqua* (GOLDFUSS) and *Myalina* cf. *bilsteinensis* ROEMER, and many gastropod

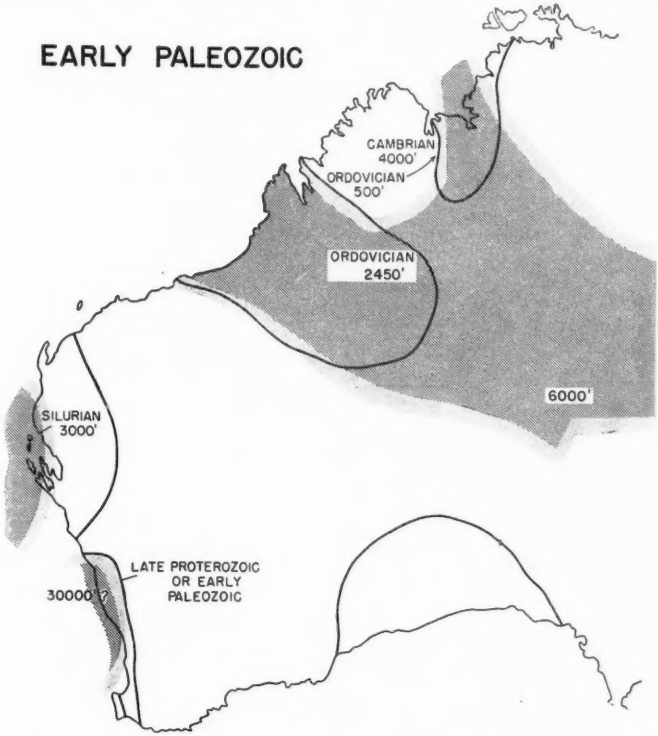

Fig. 2. Maximum extent of distribution of rocks of Early Paleozoic age in the major sedimentary basins of Western Australia. Figures indicate maximum thicknesses in feet.

genera such as *Bellerophon, Ectomaria, Bembexia, Euryzone, Straparollus, Macrochilina, Naticopsis.* In the Upper Devonian there exists a complex pattern of facies which includes conglomerates, sandstones, shales, and limestones with rich faunas of all kinds. Of considerable interest is a sequence of goniatites in which equivalents of the German Oberdevonstufen I—IV have been recognized. The *Manticoceras* zone is well represented with species of *Manticoceras, Timanites, Beloceras* and other characteristic goniatites, accompanied by *Buchiola* and the trilobites *Cyrtosymbole, Pteroparia, Drevermannia, Chaunoproetus, Harpes,* and *Scu-*

tellum. Next following are beds with *Cheiloceras, Dimeroceras*, and *Tornoceras*, equivalent to Oberdevonstufe II. Stufe III is represented by strata in which *Sporadoceras* is abundant. The succession of species of that genus closely parallels the succession from *Sporadoceras biferum* to *Sp. posthumum* as described from Germany by SCHINDEWOLF. Among

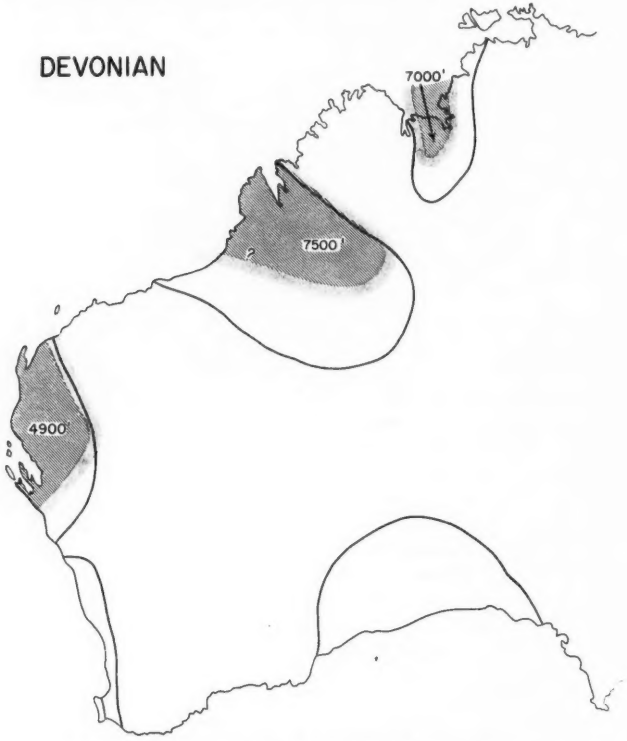

Fig. 3. Maximum extent of distribution of rocks of Devonian age in the major sedimentary basins of Western Australia. Figures indicate maximum thicknesses in feet.

associated genera is *Pseudoclymenia*. This Devonian sequence concludes with richly fossiliferous brachiopod limestones in which clymenoids occur and which are believed to be equivalent to Oberdevonstufe IV. The goniatites, clymenoids, and their associated faunas migrated to Australia from Central Germany by way of central and southeast Asia.

The Devonian of the Bonaparte Gulf and Carnarvon Basins is much less known. In the Bonaparte Gulf Basin the Upper Devonian is rather fossiliferous (MATHESON and TEICHERT, 1948; TRAVES, 1955). It is rich in

brachiopods (*Productella, Chonetes, Schuchertella, Meristella*), and gastropods (*Bellerophon, Straparollus, Platyschisma, Murchisonia,* and others), but other groups are poorly represented, and the affinities of the faunas cannot be accurately stated. In the Carnarvon Basin (TEICHERT, 1949) there are richly fossiliferous limestones with stromatoporoids, rugose

Fig. 4. Maximum extent of distribution of rocks of Mississippian (Lower Carboniferous) age in the major sedimentary basins of Western Australia. Figures indicate maximum thicknesses in feet.

corals (*Disphyllum, Hexagonaria, Thamnopora, Alveolites* — see HILL, 1954), brachiopods (*Atrypa, Hypothyridina, Productella,* and spiriferids), *Tentaculites,* and nautiloids. The spiriferids (*Austrospirifer, Cyrtospirifer*) have been described by GLENISTER (1955) and according to him are of late Frasnian age.

The first rocks of Carboniferous age (Fig. 4) in Western Australia were discovered by MATHESON and TEICHERT (1948) in the Bonaparte Gulf Basin. Shortly afterwards their occurence was detected in the Carnarvon

Basin (TEICHERT, 1949) and a thick sequence of that age has since been discovered in the Canning Basin (MCWHAE et al., ms.). Additional paleontological work has been done by ÖPIK (see NOAKES, ÖPIK & CRESPIN, 1952) and by GLENISTER (1955). Published information so far has demonstrated the presence of very early Carboniferous (Lower Mississippian) faunas in the Bonaparte Gulf and Carnarvon Basins. In the former a rich fauna has been reported, predominantly of brachiopods, including *Rhipidomella, Leptaena, Marginirugus, Tylothyris, Athyris, Composita,* in addition to corals (*Syringopora, Michelinia*), crinoids, Bryozoa, gastropods, trilobites and ostracodes. From the Mississippian fauna of the Carnarvon Basin species of *Spirifer, Punctospirifer,* and *Syringothyris* have been described.

The Lower Carboniferous rocks in the Canning Basin (THOMAS, 1957) contain a rich fauna of brachiopods (*Spirifer, Linoproductus, Composita, Camarotoechia, Eomartiniopsis?, Cleiothyridina,* and others), pelecypods, nautiloids, gastropods, conchostracans, ostracodes, in addition to some corals and sharks' teeth. The fauna indicates Tournaisian age. Upper Carboniferous from the same basin is now also known, but has not yet been paleontologically identified. Conodonts play an important part in the correlation of this series (GLENISTER, personal communication).

P e r m i a n rocks, predominantly in marine facies, are found abundantly and in great thickness in all the major Western Australian basins (Fig. 5). The greatest thicknesses are known from the Carnarvon Basin (13,000 feet) (TEICHERT, 1952; CONDON, 1955) and the Canning Basin (14,000 feet) (TEICHERT, 1947; MCWHAE et al., ms.). The sequence in the Carnarvon Basin is at present best known and most complete (TEICHERT, 1952). A general summary of distribution and affinities of Western Australian Permian faunas has been given by the writer (TEICHERT, 1951). As a rule the stratigraphic sequences begin with aqueo-glacial beds. True continental tillites may be present in the Irwin Basin (northern part of Perth Basin). Plant-bearing continental strata are intercalated with the marine beds in the Perth and Canning Basins.

The succession in the Perth Basin is of particular importance, because plant-bearing shales in which the *Glossopteris* flora (including *Gangamopteris, Vertebraria*) is associated with northern "Carboniferous" genera (*Sphenophyllum, Sphenopteris, Cladophlebis, Bothrodendron*), occur here stratigraphically well above beds with the Lower Permian ammonoids *Metalegoceras* and *Uraloceras* (CLARKE, PRENDERGAST, TEICHERT & FAIRBRIDGE 1951; TEICHERT & GLENISTER, 1952). In all basins the basal part of the Permian is poorly fossiliferous, because these are obviously cold water deposits (TEICHERT, 1941). *Eurydesma* has now at last been reported from such beds in the Carnarvon Basin (CONDON, 1956 b). In general, however, and throughout the greater part of the sections the Western Australian Permian faunas are extremely rich, although still rather incompletely known. The Foraminifera are mostly arenaceous types. Previous records of fusulinids in the Canning Basin have been found to be erroneous (BRUNNSCHWEILER, 1954, p. 44). Sponges are rare (HOWELL, 1956 b). Corals

are common in some beds, but are not generally prolific. The Tetracoralla belong to the *Cyathaxonia* fauna which includes *Plerophyllum, Euryphyllum, Verbeekiella, Amplexus, Allotriophyllum,* and *Tachylasma.* The Tabulata include species of *Favosites, Thamnopora,* and *Cladochonus.* The genera

Fig. 5. Maximum extent of distribution of rocks of Permian age in the major sedimentary basins of Western Australia. Figures indicate maximum thicknesses in feet.

Conularia and *Serpulites* of doubtful scyphozoan affinities are common in some beds. The blastoids are represented by *Rhopaloblastus* and Pterotoblastus, the asteroids by an unnamed genus. Of considerable interest are the crinoids among which the Calceolispongidae are of outstanding importance (TEICHERT, 1949, 1954). Other crinoids, less numerous, include undescribed species of the Poteriocrinitidae, Catillocrinidae, and Allagecrinidae.

The Permian Bryozoan assemblage of Western Australia is probably the richest of its age in the world, but has not yet been fully described. It is rich in cryptostomatous and cyclostomatous genera (CROCKFORD, 1957, and earlier papers by the same author). Brachiopods are exceedingly common, the productids (COLEMAN, 1957) and the spiriferids being represented by rich faunas including many large genera, such as *Taeniothaerus, Aulosteges, Waagenoconcha, Neospirifer*. Many other families are represented, but few species have been named and described.

Some years ago the writer discovered rich pelecypod faunas in the Carnarvon Basin (TEICHERT, 1941, 1951) and reported the presence of *Glyptoleda, Undulomya, Atomodesma, Parallelodon, Astartila, Allorisma, Stutchburia, Oriocrassatella, Schizodus* and other genera. He initiated a study of these faunas by DICKINS who has since described some of the forms monographically (DICKINS, 1956).

The gastropods, among which the Bellerophontids are prominent, are still mostly undescribed, and the scaphopods include undescribed species of *Plagioglyptum* and *Laevidentalium*. Among the cephalopods most nautiloids are still undescribed. These include species of *Pseudorthoceras, Mooreoceras, Domatoceras, Stearoceras, Titanoceras*, and *Phacoceras*. Ammonoidea, though generally rare, are now known from many localities in different parts of the Permian sequence and include species of *Metalegoceras, Paragastrioceras, Pseudogastrioceras, Pseudoschistoceras, Agathiceras*, and *Propinacoceras*. The trilobites are represented by *Ditomopyge*, the ostracodes by *Bythocypris, Bairdia*, and *Healdia*. Rare but important finds of fishes have proved the presence of *Helicoprion, Helodus*, and *Crassidonta*.

The Tethys affinities of this faunal assemblage are very obvious. There are many relationships with the rich, well known Permian faunas of Timor, although there is a noticeable indigenous element. On the whole, relationships between Western Australian and East Indian marine faunas in the Permian were not dissimilar to the relationships of the recent faunas of the same general areas (TEICHERT, 1951, p. 88). Recent discoveries (BANKS et al., 1955) have demonstrated the presence of Western Australian crinoids and Bryozoa in Tasmania, proving existence of a migration route south of the Australian continent.

The age of the bulk of all these faunas is Sakmarian and Artinskian. The pelecypod faunas described by DICKINS (1956) to which that author ascribes a Kungurian age underlie beds with *Helicoprion* (TEICHERT, 1952) and are, therefore, not likely to be younger than Artinskian in age. There are some, but probably few strata of post-Artinskian age in Western Australia (TEICHERT, 1947; THOMAS and DICKINS, 1954).

The lower limit of the Permian system in Western Australia is poorly defined paleontologically, because the basal aqueo-glacial and associated sediments are poorly fossiliferous. However, the faunas of the lowest fossil horizons which occur at varying distances above the base of the glacial series, are invariably typically Permian in aspect. No unmistakingly and undisputedly Carboniferous fauna has ever been found in these

beds. The *Glossopteris* flora is well represented only in the Canning and Perth Basins. Its Permian age has been convincingly demonstrated by KREMP (1954) on the basis of a study of the associated spore flora.

The Triassic system is widely represented by continental facies. In the northwestern part of the Canning Basin (BRUNNSCHWEILER, 1954) it is represented by shales which are rich in *Lingula* and *Estheria* and which have yielded remains of *Capitosaurus*, and by sandstones with a rich flora of *Thinnfeldia, Gleichenites, Otozamites,* and *Pleuromeia*. The Donnybrook sandstone, once believed to be of possible Triassic age (TEICHERT, 1947) is now known to be younger (BALME, 1957). It is obvious that much remains to be learned about the Triassic of Western Australia.

The Jurassic system is represented by rocks of continental as well as marine facies (Fig. 6). Only the latter will be considered here. Marine Jurassic rocks are now known to occur in the Perth, Carnarvon and Canning Basins. Probably the whole of the Jurassic system is represented in the Perth Basin (MCWHAE et al., ms.), but only faunas of Bajocian age are at present well known (ARKELL and PLAYFORD, 1954). They contain an ammonite fauna consisting of species of *Sonninia, Witchellia, Fontannesia, Otoites, Pseudotoites,* and *Zemistephanus*.

In the Carnarvon Basin Jurassic rocks were discovered by the writer (TEICHERT, 1939) in a very small outcrop on the Minilya River, where they were 25 feet thick. This isolated occurrence presented something of a puzzle until the recent discovery of very thick Jurassic sequences in the Northwest Cape area. Here, ARKELL (1956, p. 461) reported the presence of 1543 feet of Lower Callovian, Oxfordian?, and Berriasian or Tithonian beds. The total thickness of Jurassic rocks in this area is now believed to be at least 11,500 feet (MCWHAE et al., ms.).

From the Canning Basin rocks of Jurassic age were first reported from bores by the writer in 1939. The fauna consisted of *Buchia ("Aucella")* and *Belemnopsis* to which the writer assigned an Oxfordian to Kimmeridgian age. Later equivalent beds were found to be widely distributed in the Canning Basins. BRUNNSCHWEILER (1954) believes them to be of Tithonian age, because they are underlain by strata with *Virgatosphinctes* and *Kossmatia* of Kimmeridgian to early Tithonian age.

Cretaceous rocks (Fig. 7) have long been known from the Perth Basin where they are represented by greensands and chalk. The latter contains a rich fauna of *Uintacrinus, Marsupites, Inoceramus, Pachydiscus* and other species, indicating Santonian age. Rocks of both Early and Late Cretaceous age are represented in the Carnarvon Basin (RAGGATT, 1936; TEICHERT, 1947; CONDON, 1954; CONDON et al., 1956). They include sandstones, shales, siltstones, marls, radiolarites, and calcarenites. Presence of Cenomanian, Turonian, Santonian, Campanian and Maestrichtian equivalents has been demonstrated by analysis of rich *Globotruncana* assemblages (EDGELL, 1957). Some beds are richly fossiliferous, especially in the upper part of the series where important echinoid and ammonoid faunas occur (SPATH, 1940; CONDON, 1954, p. 117). The rich ammonoid assemblages include *Paraphylloceras, Phyllopachyceras, Pseudophyllites,*

Kossmaticeras, Diplomoceras, Glyptoxoceras, and *Eubaculites* and are Maestrichtian in age. An echinoid assemblage of *Echinocorys, Cardiaster, Cidaris, Schizaster (?), Hemiaster, Holaster, Hemipatagus (?), Phymosoma,* and *Salenia* is characteristic of beds of Danian age. These beds, and early

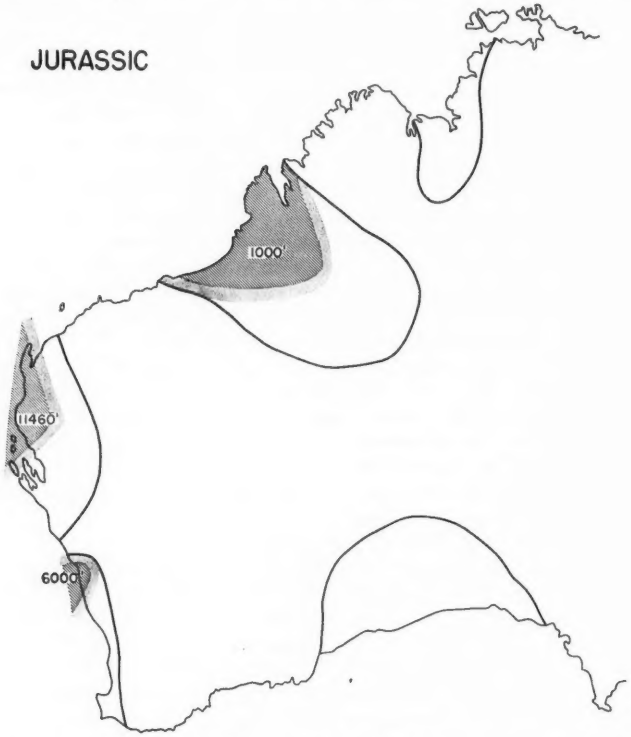

Fig. 6. Maximum extent of distribution of rocks of Jurassic age in the major sedimentary basins of Western Australia. Figures indicate maximum thicknesses in feet.

Tertiary strata, with which they are conformable have also yielded an interesting nautiloid fauna of *Cimomia, Teichertia, Aturoidea,* and *Aturia* (Glenister, Miller and Furnish, 1956).

The Cretaceous extends into the southernmost part of the Carnarvon Basin (Clarke and Teichert, 1948), but is here less fossiliferous. Thick basal sandstones (Tumblagooda sandstone), originally included in the Cretaceous, are now believed to be Paleozoic in age (McWhae et al., ms.).

Marine Cretaceous (Neocomian and possibly Aptian) is represented in

the northwestern part of the Canning Basin (BRUNNSCHWEILER, 1951) by sandstones and marls with belemnites *(Hibolites, Belemnopsis)* and pelecypods (*Meleagrinella, Cyrenopsis, Panope* and others).

The marine Cretaceous rocks in the vicinity of Darwin, Northern

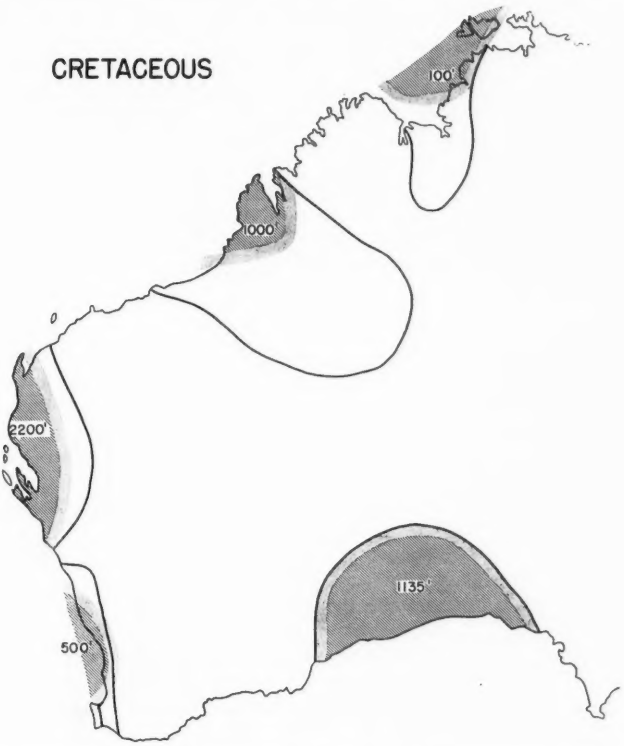

Fig. 7. Maximum extent of distribution of rocks of Cretaceous age in the major sedimentary basins of Western Australia. Figures indicate maximum thicknesses in feet.

Australia, have long been known (DAVID and BROWNE, 1950, p. 497). They lie at the northern extremity of the Bonaparte Gulf Basin and seem to be of Lower Cretaceous age. Their fauna is in need of restudy.

Marine Tertiary beds are known from the Perth and Carnarvon Basins. In the latter there is probably a continuous and conformable succession from Late Cretaceous to Early Tertiary age and near the present coast there is probably a complete sequence of marine Tertiary, followed by marine Quarternary beds (CONDON, JOHNSTONE, and PERRY,

1953). During Early Tertiary time much of the southern part of Western Australia was submerged. This transgression was long held to be Miocene in age (TEICHERT, 1944; CLARKE, TEICHERT, and MCWHAE, 1948), but an earlier (middle or upper Eocene) age now seems more probable (GLENISTER, MILLER, and FURNISH, 1956).

In summary, we find that the thick marine sequences of Paleozoic, Mesozoic and Tertiary age in the Western Australian sedimentary basins give proof of continuous presence of an open sea west of the Australian continent since Early Paleozoic time. As may perhaps be expected, the affinities of the faunas which inhabited the neritic and litoral environments of this sea along the Australian coast, are generally Tethyan, Asiatic and European. Faunistic links existed with North America (TEICHERT, 1953) in the Early Ordovician, Early Mississippian and Middle Jurassic, with central Europe in the Devonian, with Indonesia in the Permian, Upper Jurassic, and Tertiary, and with the northern surroundings of the Indian Ocean as well as with Europe in the Cretaceous.

Geotectonic relationships

In 1939, the writer suggested the name "Westralian geosyncline" for the disconnected sedimentary basins of Western Australia. Since then knowledge of these features has been enormously increased. It must be remembered that in 1939 the Bonaparte Gulf Basin had not yet been discovered, that we had no knowledge of the Ordovician and the Carboniferous, and of the true extent and thickness of the Mesozoic rocks in the Canning Basin. No rocks of Silurian, Devonian and Carboniferous age were then known from the Carnarvon Basin and the possibility of very great thicknesses of sedimentary rocks in the Perth Basin was not realized. The concept of a Westralian geosyncline has been accepted in several modern syntheses, for example by H. and G. TERMIER (1952) and W. J. ARKELL (1956). In 1947, the writer admitted that not every geologist would class the Western Australian basins as geosynclines and that they shared many features with TERCIER's paralic basins and with UMBGROVE's idiogeosynclines. In the light of our more advanced knowledge today, however, it would seem that these terms apply to much more short-lived basins, and that the Western Australian basins have more nearly geosynclinal character than was possible to predict even in 1947. Perhaps they come closest to the paraliageosynclines in KAY's terminology (KAY, 1951), but they also have some features of miogeosynclines.

Studies of the bathymetry of the eastern part of the Indian Ocean have brought out the astonishing fact that the major geotectonic features of marginal Western Australia seem to extend not only across the continental shelf, but far out into the deep sea (Fig. 1). Plotting of the 2000-fathom line by FAIRBRIDGE (1955) reveals the presence of major depressions in the deep sea floor opposite the Desert Basin and to a minor extent also opposite the Carnarvon Basin. Opposite the Pilbara Block lies the Exmouth Rise, an extensive area rising above the 2000-fathom line. These relationships

are, however, not perfect everywhere, because the Carnarvon Basin is partly blocked by the West Australian Ridge. This general continuity of continental and deep sea features need not necessarily be explained by a "break-down of former continental crustal elements" (FAIRBRIDGE, 1955), because the base of the sedimentary column in the coastal parts of the basins lies well below the 2000-fathom (= 12,000 feet) line and there need not have been any breakdown at all. Instead we may assume crustal continuity, a giant flexure, between the continent and the ocean in this part of the world. This relationship may be of very ancient date as shown by the geologic history of basins adjacent to shield. The writer has shown (TEICHERT, 1952 b, 1957) that the inner margin of the Carnarvon Basin is a largescale post-Permian flexure. Recent work in the Perth Basin, demonstrating a much greater thickness of sediments than previously expected, seems to lend support to the author's earlier suggestion (TEICHERT, 1947) that this basin, too, has a flexured eastern margin, not a faulted one as was long believed. If so, this flexure also must be very ancient.

Age of Australian continent

The continentality of Australia during much of geologic time is now an indisputable fact. Since the disappearance of the Macdonnell geosyncline in Late Ordovician time about four-fifths of the area of present continental Australia was never again below sea-level, with the exception of a short-lived epicontinental transgression in later Early Cretaceous time. It is this long-continued continentality which, before the Western Australian sedimentary basins became better known, contributed in no small measure to the picture of Gondwanaland as a supercontinent of which Australia formed the eastern promontory.

We know now that since early Paleozoic time there was an ocean to the west, transgressing over the edge of the present mainland innumerable times during the Paleozoic, Mesozoic, and Cenozoic periods, perhaps never retreating beyond the edge of the present continental shelf. In the east we had the well-established Tasman geosycline, at least throughout the Paleozoic. In the north there was Tethys and Southwest Pacific. What about the south?

Evidence of the age of the Southern Ocean south of Australia is meagre and sketchy. There are no marine deposits along the entire coast of Australia between Cape Leeuwin and Bass Strait from the time between the Late Cambrian and Early Cretaceous and existence of a southern sea during this long interval can only be deduced from faunal relationships. Dimly we recognize this Southern Ocean during Cambrian and Ordovician times. We lose its trace during Devonian and Carboniferous time. But knowledge of the faunas of this age both in Western Australia and in Tasmania is in a rudimentary stage which at present permits no conclusions about their relationships. Evidence for the early Permian faunas, however, is becoming clearer. *Eurydesma* is now known in the Carnarvon Basin. More important still is the discovery by BANKS, HALE and YAXLEY (1955)

of typical Western Australian Bryozoa and crinoids in rocks of Permian age in Tasmania.

The recent discovery of Permian arenaceous Foraminifera in claystones interbedded with fluvio-glacial sediments on Yorke Peninsula, South Australia (LUDBROOK, 1957), has been interpreted as being indicative of brackish water deltaic facies. Some of the species (e.g. *Hyperamminoides acicula),* however, are known from marine beds in Western Australia. They suggest that these deposits were laid down not far from the sea.

The evidence here cited indicates that the reality of faunal migrations along the south coast of Australia in Permian time, suggested by the writer in 1951, can no longer be doubted.

Knowledge of Triassic and Jurassic paleogeography of the southern half of Australia is very limited. During the Cretaceous period, however, the sea invaded Australia from the south.

Summing up, we recognize existence of a sea to the south of Australia as early as the beginning of the Permian period. Its existence as far back as the early Paleozoic seems to be a possibility.

Even if we had less evidence of the oceans surrounding Australia, the early isolation of this continent is evident from the meagre records of land animal life. Fifty years ago one may have been justified in pinning his faith in future discoveries of more varied land vertebrate faunas, but this is no longer possible. Following is a brief summary of land tetrapod life in Australia, essentially compiled from data given in DAVID and BROWNE (1950):

P e r m i a n : One stegocephalian, *Bothriceps major,* has been found in the Upper Permian coal measures of New South Wales.

T r i a s s i c : Stegocephalians belonging to the genera *Platyceps, Capitosaurus?, Cyclotosaurus* and *Mastodonsaurus* are known from lacustrine deposits in New South Wales, *Capitosaurus* also from Triassic rocks of the Canning Basin (BRUNNSCHWEILER, 1954).

J u r a s s i c : Saurischians *(Agrosaurus)* and two other kinds of large dinosaurs (*Rhaetosaurus, Agropelor*) are known from Queensland, also occasional footprints.

C r e t a c e o u s : A large sauropod dinosaur, *Austrosaurus,* is known from Queensland.

T e r t i a r y : GILL (1953) and STIRTON (1955) have recently shown that land vertebrate remains in rocks of Tertiary age are probably much less rare than was formerly believed. However, the only vertebrates found are marsupials.

It cannot be said that this very meagre record of past land vertebrate life is due to inadequate collecting. The Mesozoic beds of Australia contain large fish faunas, and marine reptiles have been reported from many Jurassic and Cretaceous rocks in various parts of Australia. We must, therefore, accept the fact that the first stegocephalians came to Australia in the Late Permian and that no reptiles lived there until some time in the Jurassic period, although the rich floras in Australian rocks of Mesozoic age give evidence of an abundant vegetation which could well have supported a rich reptilian life.

We may assume that earth movements in the Indonesian area very occasionally during the Jurassic and Cretaceous periods led to the chance formation of short-lived land bridges or chains of closely spaced islands by way of which a few stray reptiles were able to reach the Australian continent. Some marsupials came to Australia by a similar combination of circumstances early in the Tertiary. Just as today, the land tetrapod fauna of Australia in the past bears the stamp of long continued isolation. It consists of a few outposts of the immeasurably richer faunas which populated Asia and South Africa, especially in the Mesozoic.

The Australian record of Mesozoic land life is very much poorer than that of any other part of "Gondwanaland" as has also been pointed out by HUENE (1940) and by HAUGHTON (1954). HUENE lists 21 land reptiles from the Upper Triassic Rio do Rasto beds of Brazil. In India the first reptile appears in the Upper Permian Bijori group and about a dozen land reptiles are known from the Triassic. None of these faunas compare, of course, with those of South Africa in richness and variety.

It is interesting in this connection to note that Madagascar which became separated from the African mainland during the Permian period has only three reptiles of Permian age, none of Triassic age, (HUENE, 1940) and only one large dinosaur of Jurassic age (HAUGHTON, 1954). Here, too, geographic isolation is responsible for the impoverished land-vertebrate life.

Conclusion

The original Gondwanaland concept was founded on the belief that Peninsular India, South Africa, and Australia had in common widespread deposits of late Paleozoic age which were of continental facies and characterized by the *Glossopteris* flora. The assumption that these three lands were once united into a single large continent seemed best to explain this situation. On similar evidence the continent was extended to include South America and the South Atlantic. The size of this Gondwanaland varied greatly in the writings of different authors, but in its classical form it was believed to have embraced the area of eastern South America, the southern Atlantic Ocean, central and southern Africa, the Indian Ocean, Peninsular India, and western and central Australia. It seemed logical to conclude that such a continent should be of considerable age, although little intrinsic evidence for this existed, and its origin was sought in the Precambrian. Similarity of facies and floras in the Triassic and Jurassic rocks of the southern continents fostered the belief that Gondwanaland had existed as a continent until the Late Jurassic or Early Cretaceous. It is hardly possible to underestimate the role played by the Gondwanaland hypothesis in the development of theories of continental drift and in the formulation of various geotectonic syntheses of the present century.

During the last 20 years, however, it has been shown that the principal original premise on which the Gondwanaland concept rested is no longer true. Western Australia is not covered by continental deposits carrying

the *Glossopteris* flora. Instead there exist, along the western margin of Australia, huge sedimentary basins with geosynclinal characteristics, filled with Paleozoic and Mesozoic, predominantly marine rocks up to 40,000 feet thick. Any ideas of a former westward extension of the Australian continent across the present Indian Ocean are thus disproved. If there was a restricted Gondwanaland further west, Australia never formed part of it.

Gondwanaland is a geologic problem which stands and falls with the geologic and geophysical evidence. It may not be impossible, perhaps by still another rearrangement of the southern continents on the basis of continental drift, to make allowance for some of the facts here presented. The writer admits that he is not interested in such exercises. In evaluating a scientific hypothesis the first fundamental question is whether it is necessary at all, not whether it is possible to find facts which may be fitted into it. As regards Australia, it seems that its paleogeography, its structure and the history of its life can be satisfactorily explained without the Gondwanaland hypothesis and on the assumption that Australia was always a separate continent.

References

ABENDANON, E. C., 1919: Aequinoctia, an old Paleozoic Continent. Jour. Geol., vol. 5, p. 562—578. — ARGAND, E., 1924: La tectonique de l'Asie. XIII Congr. Géol. Intern., C. R., vol. 1, p. 171—372. — ARKELL, W. J., 1956: Jurassic geology of the World. XV + 806 p., 46 pls. New York, N. Y. — ARKELL, W. J., and PLAYFORD, P. E., 1954: The Bajocian ammonites of Western Australia. Roy. Soc. London Phil. Trans., Ser. B, Biol. Sci., no. 651, vol. 237, p. 547—605, pls. 27—40. — ARLDT, TH., 1907: Die Entstehung der Kontinente und ihrer Lebewelt. Leipzig XVII + 730 p. — BALME, B. E., 1956: Plant microfossils and the geological age of the Donnybrook sandstone. Austral. Jour. Sci., vol. 18, p. 127—128. — BANKS, M. R., HALE, G. E. A., and YAXLEY, M. L., 1955: The Permian Rocks of Woody Island, Tasmania. Pap. Proc. Roy. Soc. Tasmania, vol. 89, p. 219—229. — BEURLEN, K., 1954: La paléogéographie du continent de Gondwana. Congr. Géol. Intern., C. R., XIX sess., Alger, 1952, Sect. XIII, Fasc. XV, p. 167—192. — BLANFORD, H. F., 1875: On the age and correlation of the plant-bearing series of India and the former existence of an Indo-Oceanic continent. Quart. Jour. Geol. Soc. London, vol. 31, p. 519—542. — BLANFORD, W. T., 1896: On the papers by Dr. Kossmat and Dr. Kurtz, and on the ancient geography of Gondwana-Land. Geol. Surv. India. Rec., vol. 29, p. 52—59. — BRUNNSCHWEILER, R. O., 1951: Notes on the geology of Dampier Land, North-western Australia. Austral. Jour. Sci., vol. 14, p. 6—8. – 1954: Mesozoic stratigraphy and history of the Canning Desert and Fitzroy Valley, Western Australia. Geol. Soc. Australia, Jour., vol. 1, p. 35—54. — CARRIGY, M. A., and FAIRBRIDGE, R. W., 1955: Recent sedimentation, physiography and structure of the continental shelves of Western Australia. Roy. Soc. West. Austral., Jour., vol. 38 (1954), p. 65—95. — CLARKE, E. DE C., 1926. Natural regions in Western Australia. Roy. Soc. West. Austral., Jour., vol. 12, p. 117—132. — CLARKE, E. DE C., PRENDERGAST, K. L., TEICHERT, C., and FAIRBRIDGE, R. W., 1951: Permian succession and structure in the northern part of the Irwin Basin, Western Australia. Roy. Soc. West. Aust., Jour., vol. 35 (1948—1949), p. 31—84. — CLARKE, E. DE C., and TEICHERT, C., 1948: Cretaceous stratigraphy of Lower Murchison River

area, Western Australia. Roy. Soc. West. Aust., Jour., vol. 32 (1945—1946), p. 19—47, 1 map. — CLARKE, E. DE C., TEICHERT, C., and MCWHAE, J. R. H., 1948: Tertiary deposits near Norseman, Western Australia. Jour. Roy. Soc. West. Aust., vol. 32 (1945—1946), p. 85—103, 2 pls. — CLARKE, J. M., 1919: Falklandia. Nat. Ac. Sci. U.S.A., Proc., vol. 5, p. 102—103. — COLEMAN, P. J., 1957: Permian Productacea from Western Australia. Austral. Bur. Min. Resources, Geology, Geophysics, Bull. 40, 147 p., 21 pls. — CONDON, M. A., 1954: Progress report on the stratigraphy and structure of the Carnarvon Basin, Western Australia. Austral. Bur. Min Resources, Geology, Geophysics, Rep. no. 15, 163 p. – 1955: Explanatory notes on the Minilya 4-Mile geological sheet. Austral. Bur. Min. Resources, Geology, Geophysics, 19 p. – 1956 a: Geological occurence of oil and gas in Australia. Symp. Yacim. Petrol. y Gas, XX Congr. Geol. Intern., p. 174—184. – 1956 b: Developments in the stratigraphy and structure of Western Australia. XX Congr. Geol. Intern., Mexico, Resum. Trab. Present., p. 382—383. — CONDON, M. A., JOHNSTONE, D., and PERRY, W. J., 1953: The Cape Range structure, Western Australia. Part I. Stratigraphy and structure. Austral. Bur. Min. Resources, Geology, Geophysics, Bull. 21, p. 1—42, 15 pls. — CONDON, M. A., JOHNSTONE, D., PRICHARD, C. E., and JOHNSTONE, M. H., 1956: The Giralia and Marilla anticlines, North West Division, Western Australia. Austral. Bur. Min. Resources, Geology, Geophysics, Bull. 25, 86 p., 7 pls. — CROCKFORD, JOAN, 1957: Permian Bryozoa from the Fitzroy Basin, Western Australia. Austral. Bur. Min. Resources, Geology, Geophysics, Bull. 34, 91 p., 21 pls. — DAVID, T. W. E., and BROWNE, W. R., 1950: The geology of the Commonwealth of Australia, vol. I, London, VI + 747 p. — DICKINS, J. M., 1956: Permian pelecypods from the Carnarvon Basin, Western Australia. Austral. Bur. Min. Resources, Geology, Geophysics, Bull. 29, 42 p., 6 pls. — DU TOIT, A. L., 1937: Our Wandering Continents. Edinburgh & London, 365 p. — EDGELL, H. S., 1957: The genus Globotruncana in Northwest Australia. Micropaleontology, vol. 3, p. 101—122, pls. 1—4. — ETHERIDGE, R., JR., 1889: Remarks on fossils of Permo-Carboniferous age, from northwestern Australia, in the Macleay Museum. Linn. Soc. New S. Wales, Proc., ser. 2, vol. 4, p. 199—214, 1 pl. — FAIRBRIDGE, R. W., 1948: The juvenility of the Indian Ocean. Scope, Jour. Sci. Union Univ. West. Aust., vol. 1, p. 29—35. – 1951: Some recent advances in the geology of Western Australia. Geol. Rundsch., vol. 39, p. 284—292. – 1952: The Permian of southwestern Australia. XIX Congr. Géol. Intern., Sympos. sur les séries de Gondwana (ed. C. Teichert), Algiers, p. 136—146. – 1953: The Sahul Shelf, northern Australia; its structure and geological relationships. Roy. Soc. West. Aust., Jour., vol. 37, pl. 1—34. – 1955: Some bathymetric and geotectonic features of the eastern part of the Indian Ocean. Deep-Sea Res., vol. 2, p. 161—171. — FOORD, A. H., 1890: Description of fossils from the Kimberley District, Western Australia. Geol. Mag., Dec. III, vol. 7, p. 2—20. — FOURMARIER, P., 1937: Quelques conséquences des derniers recherches sur la géologie de Madagascar. Soc. Géol. Belg., Bull., vol. 60, p. 234—238. – 1940: Que faut-il penser de la notion de la permanence des océans? Soc. belge Etud. géogr., Bull., vol. 10, p. 25—48. — FOX, C., 1931: The Gondwana System and related formations. Geol. Surv. India, Mem., vol. 58, p. 1—241, pls. 1—8. — FRECH, F., 1902: Lethaea geognostica I. Theil. Lethaea palaeozoica, Bd. 2, Lief. 3—4. Die Dyas. Stuttgart, 354 p. — GENTILLI, J., and FAIRBRIDGE, R. W., 1951: Physiographic diagram of Australia. Geograph. Press, Columbia Univ., N. Y. — GILL, E. D., 1953: Australian Tertiary marsupials. Aust. Jour. Sci., vol. 16, p. 106—108. — GLENISTER, B. F., 1955: Devonian and Carboniferous spiriferids from the Northwest Basin, Western Australia. Roy. Soc. West. Aust.,

Jour., vol. 39, p. 46—71, pls. 1—8. — Glenister, B. F., Miller, A. K., and Furnish, W. M., 1956: Upper Cretaceous and early Tertiary nautiloids from Western Australia. Jour. Paleont., vol. 30, p. 492—503, pls. 53—56. — Guppy, D. J., Lindner, A. W., Rattigan, J. H., and Casey, J. N., 1952: The stratigraphy of the Mesozoic and Permian sediments of the Desert Basin, Western Australia. XIX Congr. Géol. Intern., Sympos. sur les séries de Gondwana (ed. C. Teichert). Algiers, p. 107—114. – 1958: The geology of the Fitzroy Basin, Western Australia. Austral. Bur. Min. Resources, Geology, Geophysics, Bull. 36, 5 pls., 5 maps. — Guppy, D. J., and Öpik, A. A., 1950: Discovery of Ordovician rocks, Kimberley Division, W. A. Aust. Jour. Sci., vol. 12, p. 205—206. — Haug, E., 1900: Les géosynclinaux et les aires continentales. Soc. Géol. France, Bull., ser. 3, vol. 28, p. 617—711. – 1911: Traité de géologie, vol. II. Paris, p. 539—928. — Haughton, S. H., 1954: Gondwanaland and the distribution of early reptiles. Geol. Soc. S. Africa, Ann., vol. 56 (Du Toit Mem. Lect. no. 3), p. 1—30. — Hill, D., 1954: Coral faunas from the Silurian of New South Wales and the Devonian of Western Australia. Aust. Bur. Min. Resources, Geology, Geophysics, Bull. 23, 51 p., 3 pls. – 1955: Contributions to the correlation and fauna of the Permian in Australia and New Zealand. A symposium by [many authors]. Jour. Geol. Soc. Australia, vol. 2, p. 83—107. — Howell, B. F., 1956 a: A new Devonian *Sphaerospongia* from Western Australia. Wagner Free Inst. Sci., Bull., vol. 31, p. 1—4, pl. 1. – 1956 b: New Permian sponges from Western Australia. Wagner Free Inst. Sci., Bull., vol. 31, p. 29—35, pls. 1—3. — Huddleston, W. H., 1883: Notes on a collection of fossils and rock specimens from West Australia, north of the Gascogne River. Quart. Jour. Geol. Soc. London, vol. 39, p. 582—595. — Huene, F. von, 1940: Die Saurier der Karro-, Gondwana- und verwandten Ablagerungen in faunistischer, biologischer und phylogenetischer Hinsicht. Neu. Jahrb. Min. etc., Beil.-Bd. Abt. B, vol. 83, p. 246—347. — Kay, M., 1951: North American geosynclines. Geol. Soc. Am., Mem. 48, 143 p., 16 pls. — Koken, E., 1907: Indisches Perm und permische Eiszeit. Neu. Jahrb. Min. etc., Festband, p. 446—546. — Kremp, G., 1954: Ein sporendiagnostischer Beitrag zum Alter der *Glossopteris*-Flora. Congr. Géol. Intern., C. R. XIX sess., Alger, 1952, Sect. XIII, Fasc. XV, p. 157—165. — Krenkel, E., 1925: Geologie Afrikas. Vol. I, Berlin, X + 461 p. — Ludbrook, N. H., 1957: Permian Foraminifera in South Australia. Austral. Jour. Sci., vol. 19, p. 161—162. — Maitland, A., Gibb, 1901: Annual progress report of the Geological Survey of Western Australia. Perth. By authority, 34 p. – 1919: A summary of the geology of Western Australia. Geol. Surv. West. Austral., Mem. 1, p. 1—55. — Matheson, R. S., and Teichert, C., 1948: Geological reconnaissance in the western portion of the Kimberley Division, Western Australia. Dept. Mines West. Austral., Ann. Prog. Rept., f. 1945, 19 p., 3 pls. — Neumayr, M., 1887: Erdgeschichte, Bd. II, Leipzig, XII + 879 p. — Noakes, L. C., Öpik, A. A., and Crespin, I., 1952: Bonaparte Gulf Basin, Western Australia. XIX Congr. Géol. Intern., Sympos. sur les séries de Gondwana (ed. C. Teichert). Algiers, p. 91—106. — Öpik, A. A., 1956: Cambrian paleogeography of Australia. El Sistema Cambrico, etc., Sympos., Pt. II. XX Congr. Geol. Intern., Mexico, p. 239—284. — Raggatt, H. G., 1936: Geology of North-West Basin, Western Australia, with particular reference to the stratigraphy of the Permo-Carboniferous. Roy. Soc. New South Wales, Jour., vol. 70, p. 100—174. — Reeves, F., 1951: Australian oil possibilities. Am. Assoc. Petroleum Geologists, Bull., vol. 35, p. 2479—2525. — Ruedemann, R., 1922: The existence and configuration of pre-Cambrian continents. New York State Mus., Bull., nos. 239—240, p. 65—152. — Salomon-Calvi, W., 1933: Die permokarbonischen Eiszeiten. Leipzig. IX

+ 156 p. — Schuchert, C., 1916: The problem of continental fracturing and diastrophism. Am. Jour. Sci., vol. 42, p. 91—105. – 1929: Review of the Late Paleozoic formation and faunas, with special references to the ice-age of Middle Permian time. Geol. Soc. America, Bull., vol. 39 (1928), p. 769—886. – 1932: Correlation of the more important marine Permian sequences. Geol. Soc. America, Bull., vol. 46, p. 1—46. — Spath, L. F., 1940: On Upper Cretaceous (Maestrichtian) Ammonoidea from Western Australia. Roy. Soc. West. Austral., Jour., vol. 26 (1939—1940), p. 41—57. — Staub, R., 1928: Der Bewegungsmechanismus der Erde. Berlin, VIII + 270 p. — Stille, H., 1924: Grundfragen der vergleichenden Tektonik. Berlin, VII + 443 p. – 1944: Geotektonische Gliederung der Erdgeschichte. Abh. Preuß. Akad. Wiss. Berlin, Math.-Nat. Kl. no. 3, p. 1—80. – 1948: Ur- und Neuozeane. Abh. Deutsche Akad. Wiss. Berlin. Math.-Nat. Kl. (1945/46), p. 1—68, 2 pls. — Stirton, R. A., 1955: Late Tertiary marsupials from South Australia. South Austral. Mus., Rec., vol. II, p. 247—268. — Suess, E., 1883—1909: Das Antlitz der Erde. Bd. I, Teil 2, p. 311—778 (1885); Bd. II, p. 1—703 (1888); Bd. III, Teil 2, p. 1—789 (1909). Vienna. — Teichert, C., 1939: The Mesozoic transgressions in Western Australia. Austral. Jour. Sci., vol. 2, p. 84—86. – 1940: *Helicoprion* in the Permian of Western Australia. Jour. Paleont., vol. 14, p. 140—149. – 1941: Upper Paleozoic of Western Australia, correlation and paleogeography. Bull. Am. Assoc. Petrol. Geologists, vol. 25, p. 371—415. – 1943: The Devonian of Western Australia. Am. Jour. Sci., vol. 241, p. 69—94, 167—184. – 1944: The genus *Aturia* in the Tertiary of Australia. Jour. Paleont., vol. 18, p. 73—82, pls. 14—16. – 1947: Stratigraphy of Western Australia. Am. Assoc. Petroleum Geologists, Bull., vol. 31, p. 1—70. – 1949 a: Discovery of Devonian and Carboniferous Rocks in the North-West Basin, Western Australia. Austral. Jour. Sci., vol. 12, p. 62—65. – 1949 b: Observations on stratigraphy and palaeontology of Devonian, western portion of Kimberley Division, Western Australia. Austral. Bur. Min. Resources, Geology, Geophysics, Rept. no. 2, 55 p., 6 pls. – 1950: Some recent additions to stratigraphy of Western Australia. Am. Assoc. Petroleum Geologists, Bull., vol. 34, p. 1787—1794. – 1951: The marine Permian faunas of Western Australia. Palaont. Zeit., vol. 24, p. 76—90. – 1952 a: A brief history of the Gondwanaland concept and of the International Gondwana Commission. XIX Congr. Géol. Intern., Sympos. sur les séries de Gondwana (ed. C. Teichert), Algiers, p. 7—12. – 1952 b: Carboniferous, Permian, and Jurassic in the Northwest Basin, Western Australia. XIX Congr. Géol. Intern., Sympos. sur les séries de Gondwana (ed. C. Teichert). Algiers. p. 115—135. – 1953: Some trans-Pacific Paleozoic correlations. Bull. Am. Geol. Soc., vol. 64, p. 1516—17. – 1954: A new Permian crinoid from Western Australia. Jour. Paleont., vol. 28, p. 70—75, pls. 13, 14. – 1957: Notes on the geology of the Carnarvon (Northwest) Basin, Western Australia. Roy. Soc. West. Austral., Jour., vol. 40, p. 65—72. — Teichert, C., and Glenister, B. F., 1952: Lower Permian ammonoids from the Irwin Basin, Western Australia. Jour. Paleont., vol. 26, p. 12—23, pls. 3, 4. – 1954: Early Ordovician cephalopod fauna from northwestern Australia. Bull. Am. Paleont., vol. 35, no. 150, 91 p., 10 pls. — Termier, H., and Termier, G., 1952: Histoire géologique de la Biosphère. Paris. 721 p. — Thomas, A. G., 1957: Lower Carboniferous deposits in the Fitzroy Basin, Western Australia. Austral. Jour. Sci., vol. 19, p. 160—161. — Thomas, A. G., and Dickins, J. M., 1954 a: Correlation and age of the marine Permian formations of Western Australia. Austral. Jour. Sci., vol. 16, p. 219—223. – 1954 b: Discovery of Upper Devonian Rocks in the Pelican Hill Bore. Austral. Jour. Sci., vol. 17, p. 47—50. — Traves, D. M., 1955: The geology of the Ord-Victoria region, Northern Australia. Austral. Bur. Min. Resources,

Geology, Geophysics, Bull. 27, 133 p., 3 pls. – 1956: Upper Proterozoic and Cambrian geology in northwestern Australia. XX Cong. Geol. Intern. Mexico, El Sistemo Cambrico, etc., Sympos., Pt. II, p. 75—90. — WEGENER, A., 1929: Die Entstehung der Kontinente und Ozeane. 4th ed. Braunschweig, X + 231 p. — WILLIS, B., 1932: Isthmian links. Geol. Soc. Am., Bull., vol. 46, p. 771—776.

SAKMARIAN GEOGRAPHY

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With 8 Figures

Abstract

The known palaeontological and stratigraphical evidence is used as a basis for the construction of maps of the continents showing the extent of their inundation by the sea in Sakmarian time in the Upper Palaeozoic. In the northern hemisphere apart from India the evidence is sufficiently reliable to give reasonable maps, and the great extent of the inundations suggests that the climate would be considerably modified from that of today; no undoubted Sakmarian glacials occur there. In Southern continents and India, the "Gondwana" biogeographical province has made correlation with the northern continents controversial, but reasons are given for assuming that "Gondwana" glacial deposits were at least in part Sakmarian; the resultant maps show that the "Gondwana" land surfaces were but little reduced in area, and that the main glacials (except for India) lie within a belt between 40° S and 20° S. Present lack of knowledge of Sakmarian conditions in Antarctica makes reconstructions of climatic belts too hazardous for possible use in enunciating or checking hypotheses of continental drift and polar wandering.

This paper offers provisional maps showing the land and sea surfaces deduced from the known sediments, fossils and earth movements for as short as possible a period of geological time during the upper Palaeozoic glaciation. Where knowledge warrants, the text discusses the relief of the land. The time chosen is the Sakmarian. Obviously the first essential is the reliable correlation of the strata used, from basin to basin, and from continent to continent, and the Sakmarian is particularly interesting but difficult, because of the apparent development of distinct biogeographical provinces — "Gondwanaland" and the continents of the Northern Hemisphere.

Factors affecting surface temperature in the past (as now) in different parts of the earth are numerous; but they include some about which only Historical Geology can supply evidence, such as the relation between land and sea surfaces and the relief of the land. These together affect the atmospheric and oceanic circulation; the former is the more important in weather and climate, but the latter is important in the migration of marine species. FLOHN (1952 Geol. Rundsch. p. 153) has brought to the attention of geologists modern three-dimensional studies on the atmospheric circulation in relation to land and sea surfaces, relief, and weather and climate. He indicates that glaciation under present day and Pleisto-

cene conditions is favoured by meridional types of circulation as against zonal types, and that in the N. Hemisphere there is a relation between the magnetic poles, the quasi-stationary high-level troughs of the meridional circulation and the centres of glaciation. He suggests that past glaciations may best be explained by fluctuations in solar radiation combined with increases in meridional type circulation due to variations in the surface relief of the earth.

If we wish to examine the upper Palaeozoic glaciation in the light of modern ideas on orography and three dimensional atmospheric circulation or vice versa, or to assess current geophysical speculations on the wanderings of the pole or continental drift, obviously a first requirement is a palaeogeographic world map that is as accurate as Historical Geology can make it. We must know what these speculations are required to explain. The maps presented here are offered primarily to historical geologists for improvement; when we are reasonably agreed upon emended maps, these can be used in the meteorological and geophysical speculations, either to check on a given hypothesis, or to help in formulating an hypothesis.

That period of the earth's history arbitrarily known as Sakmarian time takes its name from a series of sediments deposited in the environs of the Sakmara River, a tributary entering the Ural River at Chkalov (olim Orenburg) on the South West slopes of the Ural Mountains. The limits and equivalence of the Sakmarian, even in Russia, are still somewhat fluid, and to give some fixity for this essay I have arbitrarily taken the limits given by RUZHENTSEV (1954, 1956) the Russian cephalopod specialist, which appear to be accepted also by SHIMANSKY (1954), ROZOVSKAYA (1949) and MAXIMOVA (1952). These are from the top of RUZHENTSEV's Orenburgian stage to the base of his Artinskian stage; the Sakmarian stage thus includes RUZHENTSEV's Asselian and Sakmarian substages, the latter (and upper) being divisible into the Tastuba and Sterlitamak horizons. It would thus seem to include DUNBAR's (1940, 1942) usage of Sakmarian and upwards to the base of the beds with *Parafusulina lutugini;* and in these extended limits it appears to be almost exactly equivalent to the Wolfcampian of North America (RUZHENTSEV, 1956). RUZHENTSEV earlier had grouped the Sterlitamak horizon in the Artinskian.

Invertebrate palaeontologists have done their most precise work for this general time on goniatites, fusulines and corals, neglecting, unfortunately, the brachiopods which are to be found almost everywhere. Goniatites are common only in the Urals and North America; fusulines are common in North America, the Urals, Eurasiatic Tethys and South East Asia, and corals are common only in the Urals and in Eurasiatic Tethys. Floras show marked geographic preferences also, while vertebrate remains are not common enough for extensive use.

Using goniatites, fusulines and corals, reasonably safe correlations have been found between Europe and Asia on the one hand and North America on the other; but the correlations with and within Gondwanaland (the southern continents and India) are far from secure, and one looks

for improvement to future intensive subgeneric work on the brachiopod and lamellibranch faunas of both hemispheres and particularly of south and central America, and West Australia and Indonesia, where the Gondwanan and other faunas come closest together geographically. In the sections on Europe, Asia and North America I have not discussed the correlations of strata nor the reasons for them, on which the maps offered are based, as these correlations are familiar in the relevant areas; but I have given more detail for southern continents.

It might be helpful to give lists of the genera known at present in the Sakmarian (of RUZHENTSEV) in Russia.

Goniatites (generic diagnoses as by RUZHENTSEV 1951, 1954, 1956):

1. Lasting from pre-Sakmarian times into the Asselian substage only, *Aristoceras, Eosianites, Glaphyrites, Neoaganides, Neoglyphyrites.*
2. Lasting from pre-Sakmarian times through the Asselian into the Sakmarian substage only, *Boesites, Daixites, Metapronorites, Prothalassoceras, Somoholites.*
3. Lasting from pre-Sakmarian into post-Sakmarian times, *Agathiceras, Artinskia, Kargalites (Kargalites), Marathonites (Almites), Neopronorites.*
4. Confined to Asselian substage, *Protopopanoceras, Shikhanites.*
5. Confined to Asselian and Sakmarian substages, *Akmilleria, Juresanites, Properrinites, Prostacheoceras, Tabantalites.*
6. Confined to Sakmarian substage, *Preshumardites, Propopanoceras, Synartinskia, Synuraloceras.*
7. First appearing in Asselian substage and continuing into post-Sakmarian times, *Paragastrioceras, Sakmarites, Waagenina.*
8. First appearing in Sakmarian substage and continuing into post-Sakmarian times, *Crimites, Medliocottia, Metalegoceras, Thalassoceras, Uraloceras.*

MILLER and FURNISH (1957 in [L] Mollusca 4 of the Treatise on Invertebrate Paleontology) have placed 20 of these genera in synonymy with earlier genera, but RUZHENTSEV's narrower definitions are used herein since they appear to have stratigraphic value in the standard sequences in Russia. On MILLER and FURNISH's definitions, the Russian Sakmarian would contain *Eothalassoceras, Eoasianites, Imitoceras, Boesites, Prouddenites, Neopronorites, Thalassoceras, Agathiceras, Artinskia, Peritrochia, Propopanoceras, Properrinites, Synuraloceras, Paragastrioceras, Stacheoceras, Crimites, Medliocottia, Metalegoceras* and *Pseudogastrioceras.*

Nautiloids in the Urals (generic diagnoses of SHIMANSKY, 1954, RUZHENTSEV and SHIMANSKY, 1954).

1. Known in Asselian but not later, *Belemnitomimus, Cycloceras, Kionoceras, Tabantaloceras.*
2. Known in Asselian and extending into Sakmarian substage: *Bactrites.*
3. Known in Asselian and extending into post-Sakmarian times, *Bitaunioceras, Ctenobactrites, Dolorthoceras.*

4. Known only in the Tastuba horizon of the Sakmarian substage, *Simorthoceras.*
5. Entering in the Tastuba horizon and continuing into post-Sakmarian times, *Gzheloceras, Mooreoceras, Pseudorthoceras, Rhiphaeoceras, Sholakoceras, Uralorthoceras.*
6. Entering in the Sterlitamak horizon of the Sakmarian substage and continuing into post-Sakmarian times, *Dentoceras, Hemibactrites, Mariceras, Mosquoceras, Scyphoceras.*

Fusulinids in the Urals (list not exhaustive, generic diagnoses as by ROZOVSKAYA and other Russian authors):

1. Not known above Asselian substage of the Sakmarian, *Pseudoschwagerina, Triticites (Jigulites), Triticites (Rauserites).*
2. Extending through the Asselian and Sakmarian substages into post-Sakmarian times, *Pseudofusulina* (very numerous species), *Rugosofusulina, Schwagerina.*
3. Not appearing in the Sakmarian, but common in the Aktastian (lower) substage of the Artinskian, *Parafusulina.*

Rugose Corals (generic diagnoses as by FOMICHEV, 1953) *Amplexocarinia, "Campophyllum", "Caninia", Caninophyllum, Timania* and the colonial *"Diphystrotion", [Dobrolyubovia], Eolithostrotionella, [Gorskya], Protowentzelella* and *Tschussovskenia.* All except *Protowentzelella* are known in the Orenburgian or earlier stages, and all except *"Campophyllum"* continue into the Artinskian. The Russian colonial Rugose genera are provincial; none have been certainly identified elsewhere. I do not know if type species have yet been named for the genera cited in square brackets.

Europe

Judging from the outcrops of strata carrying known Sakmarian fossils, the dominating region for marine sedimentation was the meridional Ural geosyncline. From this, epicontental (shelf) seas spread westerly into the Moscow Basin, the Donetz Basin and the Crimean Gulf; to the south (probably around the Caspian Sea), the Ural geosyncline presumably joined Tethys, the Mediterranean of the time; and to the north, the Polar Sea.

The Sakmarian shelf sea spreading on to the Moscow Basin reached at least as far west as the Oka uplift (IGNATIEV, 1952), but may have been less extensive than earlier, Moscovian and Dinantian seas. Terrigenous material is scant in the Sakmarian deposits of the Moscow Basin, leading to the conclusion that the exposed areas of and around the Russian platform were of very low relief. The thin limestones of the Moscow Basin expand at the hinge region with the Ural geosyncline, and organic reefs grew at the edge of the shelf, from about 65° N to at least 48° N, where the Palaeozoic rocks of the Urals disappear under Mesozoic and Tertiary cover. These reefs contain corals, but cannot be called coral reefs; the dominant organisms were brachiopods, polyzoa, crinoids, forams and

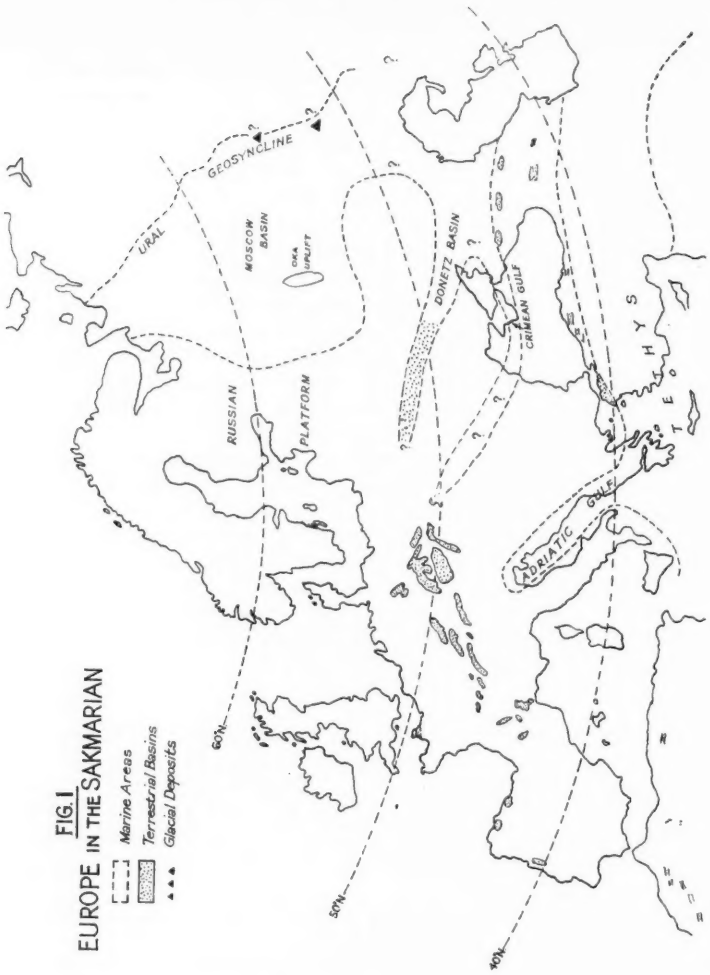


FIG. I
EUROPE IN THE SAKMARIAN

algae (TOLSTIKHINA, 1937). Whether they indicate similar minimal sea surface temperatures to the coral reefs of today (16° C) is arguable.

In the Ural geosyncline itself, limestones give place eastwards to argillaceous and arenaceous sediments, derived from rising mountains fronting its eastern boundary.

The Moscow Basin seems to have been separated from the Donetz Basin by a massif of older rocks. The Donetz Basin is a relatively narrow

trough; Sakmarian deposits in it are mainly gypseous dolomites, sandstones and shales, and seem to indicate less free circulation of the marine waters than formerly. A study of bore cores and river-bed rock bars has suggested that the Donetz Basin continued far to the W.N.W. almost to Pinsk, though no Sakmarian marine strata have been recognised as such in this underground extension (SUJKOWSKI, 1946).

The Crimean Gulf is separated from the Donetz Basin by an Archaean massif though the two probably joined in the east before meeting the Ural Geosyncline in the area of the Caspian Sea. Its Sakmarian sediments are argillaceous mainly, rich in goniatites (TOUMANSKY, 1937). It may conceivably have continued to the N.W., more or less parallel with the Donetz extension, to supply marine waters to the Carpathian region (Bükk Mountains and Dobsina, RAKUSZ, 1932), but there is no actual evidence for this. The facies of the Carpathian deposits is rather like that of the Adriatic Gulf.

The Crimean Gulf is separated from the more or less parallel trending Tethys by Caucasian fold mountains. Tethys lay across Asia Minor except along the north, left calcareous deposits in many places in Anatolia, in the Aegean Isles, and in southern Greece, and sent an arm up the Adriatic Sea to front on the Carnic Alps with an eastern shore in Dalmatia. The *Schwagerina* — limestone banks were formed in this sea, though much argillaceous matter was poured in also (HERITSCH, 1939). These banks, which are possibly analogous to the "reefs" of the Urals, are known as far north as 47°.

How Tethys joined the Atlantic Ocean in Sakmarian times is not known, for no Sakmarian fossils are known in the western Mediterranean. Such a junction seems called for, however, to explain faunal similarities with North America.

The entire European Sakmarian is characterised by rich fusuline faunas; goniatites are common, brachiopods are often numerous, and corals occur. All the marine deposits may be considered of one major faunal province, though the Carnic Alps fauna is somewhat different from that of the Urals.

It should be noted that within Sakmarian deposits near the Sim Works in the Urals, in latitude 55° N approximately, the Dommenaya Breccia was regarded by NALIVKIN (1937) as a marine glacial deposit, dropped from icebergs. DUNBAR (1940) however, regards it as a landslide breccia related to submarine faulting. Similar breccias occur in the Orenburg region (52° N approximately), and BACKLUND (1930) drew attention to a possible late-Palaeozoic tillite in the Kara River area, N.W. Urals.

As for that part of Europe not covered by the sea, we can distinguish two main regions:— the regions where no folding later than Caledonian had occurred, and the regions affected by the Variscan orogenies. The former regions are those of the western part of the Russian Platform, Scandinavia, and most of the British Isles, and on these, continental sediments equivalent in age to the marine Sakmarian are thin and unimportant, or unknown. We may deduce that relief was slight over these areas.

Variscan orogenies, including the Asturian phase, which was probably just pre-Sakmarian, affected Spain and Portugal, France, Germany, Austria and Czechoslovakia and the eastern Balkan States. Detritus from the uplifted areas was washed down and deposited in two types of basins, one, inland, well above sea level, the limnic basins; and the other, paralic basins on coastal plains, subject to inundations by small changes of sea level. Most of these basins in existence in Sakmarian times were relics or extensions from the highly important coal basins of earlier Carboniferous times. Palaeobotanists have shown that the fossil floras of the two types of basin were distinct, and formed two different types of the swamp flora at that time characteristic of Europe and North America, particularly eastern North America (JONGMANS, 1952 a, 1952 b). In the inland basins of France, the deposits which palaeobotanists now equate with the Sakmarian are generally called Autunian, and in Germany the Lower Rotliegende. Coal seams are few, in contrast to the wealth of middle and early Upper Carboniferous times, and many of the beds (conglomerates, sandstones and shales) are red in colour, though green and violet beds also occur. In the opinion of palaeobotanists, these features indicate a period of gradually increasing aridity, though the whole of Europe had not been reduced in rainfall to that low level characteristic of later Permian times. It was a time of transition.

Thus the topography of Europe during the Sakmarian is fairly clear. A meridional sea lay in the east, a mediterranean sea in the south. From the eastern sea, shallow bodies of water spread on to low lands in the north east and central east, and along the feet of mountains in the south. The continent may have extended out beyond its present western and northern shores, possibly as far as the 2000 metre line. The northern and eastern part was of very low relief, the western and southern parts of high relief with intramontane basins.

Rainfall was probably seasonal, not of the rain belt type, for coal swamps were rare. The red colour of the terrestrial sediments could indicate either laterite soil conditions, or conditions of alternate flood and drying out, oxidation of iron occurring during drying out. If redistributed laterite soils were widely prevalent, rainbelt conditions could be assumed in the period preceding the Rotliegende, but would scarcely be arguable for the Sakmarian itself.

Several lines of attack on the problem of climatic zones have been suggested in the Sakmarian literature, but none of them have been taken up sufficiently widely yet to yield any valuable results. It has been suggested that if the Rotliegende were derived from erosion of laterite soils, the Rotliegende clays should be of types appropriate to this origin. Seasonal rings in trees have been investigated in a few isolated instances. Possibly a greater knowledge of temparate and tropical peats than we have at present will prove applicable to the study of Autunian coals (FRANCIS, 1954). So far, however, I have found nothing on these lines in the literature on which one can base sound palaeoclimatic argument.

In the marine sediments, the predominance of limestones and especially the development of organic reefs has been used as an argument for the tropical to subtropical temperature of the Ural geosyncline waters. But the limestone of the Moscow Basin may only be a reflection of the lack of terrigenous matter supplied from the Russian platform. Brachiopod — polyzoan — algal reefs may conceivably form in temperatures lower than the coral reefs of today. The fusulines, being larger forams, and developed in great numbers, are often regarded as typical warm-water forams, but no fusulines are alive today, and the argument from analogy is not very strong.

Table 1. RUZHENTSEV's subdivision of the Sakmarian stage in the Southern Urals.

Artinskian Stage		
Sakmarian Stage	Sakmarian substage	Sterlitamak horizon Tastuba horizon
	Asselian substage	
Orenburgian Stage		

Table 2. Approximate equivalents of Sakmarian in Northern Hemisphere.

N. America	Europe marine	Europe terrestrial	Asia
Leonardian	Artinskian	U. Rotliegende	Amb Group
Wolfcampian	Sakmarian	L. Rotliegende and Autunian	Warcha Group. Talchir Group. (also Taiyuan Fm. in N. China and Maping and Chuanshan Fm. in S. China
U. Pennsylvanian	Orenburgian	Stephanian	

Asia

Sakmarian Asia appears to have been land north of 45° N except perhaps for marginal seas in Ussuriland and for a narrow (Taimyr) trough along the southern edge of the Kara Sea massif, in about 73°—75° N and 80° to 115° E (OBRUTSCHEW, 1926) rich in brachiopods (LIKHAREV, 1937; USTRISHKY, 1955). In the West this land (Angaraland) was separated from the Russian platform by the Ural geosyncline. It was probably of low or moderate relief in the north, with some fold ranges near its southern borders. Great basins of coastal plain type, not far above sea level, were present along the southern coast line, such as the Basins of Kusnetsk and Minussinsk. In some of these basins, short inundations of the sea occurred in Gshelian (Orenburgian) times, and even, perhaps, in Sakmarian time, though no satisfactory proofs of the latter exist. To the north, in the Tunguska, a great inland basin was present, unproductive of coals, rather like the Great Artesian Basin of Australia today. The flora found in the basins of Angaraland is a swamp flora of distinct province, the Angara

flora, and seems to have had little or no connection with that of Europe or India or N. America. The non-marine lamellibranchs too are very different (WEIR, 1945). The sediments forming in Sakmarian (Autunian or Rotliegende) time are consequently difficult to identify, but if we follow JONGMANS (1939, 1952) they are those of the Ungian and Koltschugian and their equivalents; if we follow TSHIRKOVA and ZALESSKY (1939) they are those of the earlier Tomian and Abian Stages. These sediments in the latitudes of the forties contain productive coals. It would thus seem that precipitation was sufficiently great, or drainage sufficiently poor, to support peat swamps in latitudes 40—45° N in these times, and one gathers that Asia in these latitudes had better rainfall than Europe. Whether they were temperate peats or tropical peats is not yet clear. The only record of possible Sakmarian glacials in Angaraland is by NORIN (1930) in the Kuruk-tagh Mts. (between 88°—90° E and 40—42° N).

South of Angara lay a great mediterranean sea. This may have been connected with the Ural geosyncline, but evidence is lacking owing to Mesozoic and Tertiary cover; the connection, if any, seems to have been broken by Zechstein (Kazanian) times. Whether the Ural connection existed or not, Asiatic Tethys was continuous with the Asia Minor part of European Tethys through southern and western Iran, Baluchistan and Afghanistan (DOUGLAS, 1950; STOYANOW, 1942; THOMPSON, 1946); but whether this connection stretched northwards to the northern boundary of Iran and Afghanistan is still unclear; there may indeed have been two seas, one in the south and one in the north, but direct evidence in the form of Sakmarian fossils is absent in the north (HERITSCH, 1939).

Along meridian 70° E, this Sakmarian sea stretched from the Salt Range northwards to Ferghana, possibly with some island arcs within it parallel to its shorelines. The Salt Range deposits seem to be shelf deposits, the deeper parts of the sea lying to the north. North of Ferghana Variscan fold mountains occurred, but coal swamps lay in places between them and the sea (OBRUTSCHEW, 1926; LEUCHS, 1935).

From this wide sea in the vicinity of 70° E, there extended eastwards two short arms and one very long one, the shortest in the north. Here a sea which we might call the Dzungarian sea stretched some distance towards Urumchi in Dzungaria along the N. rim of the Tarim massif, but was only a fragment of the former Viséan and later *Neoschwagerina* seas which stretched from Dzungaria into the Mongolian Basin and thence to the Pacific (GRABAU, 1931, KAHLER, 1940, MINATO, 1953, KOBAYASHI, 1952). No certain Sakmarian marine fossils are known east of Urumchi district; and large areas of rather flat lying land were added to Angara in Sakmarian time, including the Mongolian geosyncline.

A middle or Nan Sea stretched from the Pamirs eastwards around the S. rim of the Tarim Basin, and north of the Tibetan massif, along the Nan Shan region, transgressing northwards on to the Tarim massif almost as far as Yarkand and Cherchen (OBRUTSCHEW, 1926, LEUCHS, 1935). Marine Sakmarian with fusulines is known from north of the Koko Nor and S.E. of Suchow, and it is possible that this sea was in intermittent

FIG.2
ASIA IN THE SAKMARIAN

Marine Areas
Terrestrial Basins
Glacial Deposits

TUNGUS
BASIN
Ussuri Sea
Sea
HEINAN GEOSYNCLINE
Land
Sea
HUANGHO BASIN
YANGTZE BASIN
Land
TETHYS
Cancer
Sea
Land
Sea
Sea
Land

connection eastwards, through the Huangho Basin, with the Taiyuan sea of N.E. China (Kobayashi, 1952).

The third great sea is Himalayan Tethys, which curved eastwards from Kashmir through the Himalayan region into W. China, perhaps with shallow extensions northwards on to the Tibetian massif. In W. China (Dunbar and Misch, 1947) it became continuous with shallow seas over the Yangtse Basin, and with geosynclines which ran southerly through Burma and Indo-China (Fromaget, 1952).

This sea and its deposits are of great importance to Sakmarian correlation, for it lies along the northern shore of the Indian portion of Gondwanaland, and *Eurydesma,* one of the most important and characteristic lamellibranch elements of the Gondwana marine fauna occurs in its deposits in the Salt Range and eastwards. In the lower parts of the Salt Range sequence, goniatites, fusulinids and corals that might be used to tie the sequences in with the Eurasian Sakmarian, are absent; the only help we get from these groups is in the upper part of the Amb Group in the Lower *Productus* limestone, where *Parafusulina kattaensis* (Waagen) is generally considered to indicate an Artinskian (Leonard) age for this limestone (Dunbar, 1933). Beneath this lie dark sandy brachiopod limestones with interbedded clays, with the N. Hemisphere genus *Richthofenia,* which Gerth (1950) considers Artinskian. *Richthofenia* is not known in the Gondwana faunas. Below this again is the Warcha Group of brown clays and speckled sandstones, olive sandstones and clays with concretions, with the Gondwana association *Eurydesma* and *Conularia* and the plants *Glossopteris* and *Gangamopteris.* Beneath lies the Talchir Group of tillites and melt water deposits. Gerth (1950) regards both Warcha and Talchir groups as Sakmarian, and in the absence of evidence to the contrary, this seems reasonable. It is important to realise however, that the Sakmarian age for the Talchir Boulder Beds here is not strictly determined, but rests on inference, the Beds lying stratigraphically below the Lower *Productus* limestone which on the strength of one fusulinid species is regarded as Artinskian. If the Tillites are continental moraines, the *Eurydesma* fauna must have invaded the land on the waning of the ice.

In Kashmir, no sign of glacial deposits is seen, but instead vast quantities of volcanic materials appear, part of which (Agglomeratic Slate Series) is generally correlated with the *Eurydesma* Beds of the Salt Range; the Gondwana brachiopod *Taeniothaerus* occurs also, and adds to the evidence for the existence of the Gondwana marine fauna along the southern shore of Himalayan Tethys, possibly, as we have seen, in the Sakmarian. No fusulines occur on this shore. Eastwards from Kashmir and the Salt Range, no distinctive fossils are known in the Indian beds that are correlated with the Sakmarian (Wadia, 1953).

India south of the Himalayas was continental throughout Sakmarian times except for a small seaway to Umaria, in which brachiopods and possibly *Eurydesma* lived (Thomas, 1954), its marine deposits overlying glacials. Continental glacial beds, the Talchirs, occur today in 3 main

lines of outcrop (WADIA, 1952), meeting roughly in the vicinity 30° N and 20° N, the arrangement suggesting great valley deposits from huge mountain glaciers; that Indian glaciation was not of the continental ice sheet type, but of alpine type, appears to be the view of FOX (1937), and JACOB (1952), and is a view that I accept. Glaciated pavements are known in Rajputana, but the age of the glaciation is unknown; the rocks glaciated are Pre-Cambrian, so the high mountains could scarcely have been fold mountains. The *Glossopteris-Gangamopteris* flora, it seems, did not appear till the highest of the glacial beds were deposited, and many, therefore, not have entered until the succeeding amelioration of climate. This Indian flora, the typical "Gondwana" flora, has nothing in common with those of Europe and North America, so that it cannot be dated by reference to them.

In placing both the Salt Range and Indian glacials in the Sakmarian we may easily be in error. Possibly maps should be constructed showing them as Orenburgian and Moscovian as well, to see into which pattern they fit best.

The *Schwagerina* facies of Iran, Baluchistan (DOUGLAS, 1950), Chitral and the Pamirs (DUTKIEWICZ, 1937), also known in the Dzungarian and Nan Seas (THOMPSON and MILLER, 1935), is seen again in the Himalayan Sea in the N. Shan States (CHIBBER, 1934), and in this area the E. Asian Sakmarian seas meet the Himalayan Sea.

In E. Asia (except Indo-China) two main basins of Sakmarian deposition may be recognised — the Huangho, and continuous with it over the extension of the present Nan Shan, the Yangtse Basin, which merged westward with the Himalayan Sea, and opened into the Japan Sea through S. Korea. An arm of the Huangho Basin, closed eastward, extended N. E. from the head of the Gulf of Laiotung (KOBAYASHI, 1942, 1952). The Huangho Basin opened into the Japan Sea by the Heinan geosyncline across N. Korea. Japan was inundated, probably completely, during Sakmarian times, and fusulinid limestones are common (MINATO, 1955) but no goniatites are known (HAYASAKI, 1954). Sakmarian deposits follow an Orenburgian period of non-deposition or emergence in most parts of Japan.

Sakmarian deposits of the Yangtse Sea were epicontental limestones rich in fusulines and corals, with some interbedded shales — the Maping and Chuan Shan limestones. In the Huangho Basin, the Taiyuan Formation (Huangchi) is paralic, with coal measures interbedded with limestones rich in fusulinids and productids (LEE, 1939). The Huangho sea may have breeched the barrier into E. Mongolia in the vicinity of Hsin King (ENDO, 1953).

The development of coal measure swamps in the Huangho Basin shows that this was a region of high rainfall. Such deposits are not known in the Mongolian geosyncline, whose relief may not have been suitable for swamps to form, or which perhaps lay north of the rainfall belt.

In Ussuri Land (vicinity of Vladivostock and northwards along the coast) ?*Taeniothaerus* of the Kashmir and Australian Sakmarian may occur

(GRABAU, 1931), with other forms regarded as "southern, cold water" forms by FREDERICKS.

No Sakmarian deposits are known from the Philippines, which were probably land at the time (VAN BEMMELEN, 1949); most of Indonesia and New Guinea appear to have been land also (VAN BEMMELEN, 1949), though marine deposits rich in Sakmarian ammonites and with some fusulines are known from Timor and Sumatra (GERTH, 1950; THOMPSON, 1936, 1949), and some Permian smaller forams and brachiopods have been recorded from the Western Highlands of New Guinea (RICKWOOD, 1955; GLAESSNER, LLEWELLYN and STANLEY, 1950).

North America

Most of the present land areas north of the Arctic Circle seem to have been emergent during the upper Palaeozoic, but no Upper Palaeozoic glacials are recorded therefrom, and there is no evidence bearing on the height at which the land stood. The only marine Sakmarian identified with reasonable certainty is in Ellesmereland, in a S.W.—N.E. belt through Greely Fjiord (TROELSEN, 1950), where 2000 feet of impure limestones with *Schwagerina* alternate with shales and sandstones and lie discordantly on mid-Pennsylvanian marine beds; there are no coral reefs, but some brachiopod and polyzoan biostromes. This sea extended N.W. on to Axel Heiberg I., where volcanics are interbedded with its limestone deposits.

In N.E. Greenland, there is in Peary Land, Holm's Land and Amdrup's Land a thin narrow fringe of marine conglomerates, red and grey sandstones and marly shales with limestones containing fusulines followed by dolomitic and in part silicified limestones; these may be in part Sakmarian (THOMPSON, WHEELER and HAZZARD, 1946; FREBOLD, 1950; TROELSEN, 1950) or in part Zechstein (DUNBAR, 1955). In central E. Greenland, similar rocks formerly (FREBOLD, 1950) regarded as Sakmarian are now all referred to the Zechstein (= Kazanian) (DUNBAR, 1955).

W.S.W. from Southern Ellesmereland stretches a narrow belt of Upper Palaeozoic sediments, through Byam Martin, Melville and Bathurst Islands (FORTIER, MCNAIR and THORSTEINSSON, 1954); white non-marine sandstones with coals are overlain by limestones and possibly Sakmarian deposits are represented in the sequence. The 300 ft. Sadlerochit sandstone with marine fossils in the Canning River and U. Porcupine River areas of N.E. Alaska may represent a continuation of this Parry Island Belt.

In cold temperate Canada and Alaska all but a Pacific belt some 500—600 miles wide was emergent in post-Mississippian Palaeozoic time. No glacials are recorded, and there is no evidence bearing on the height of the land. This belt seems divisible into two, the boundary lying along the Kuskokwim River in Alaska and in the Canadian Rocky Mt. Trench. In the outer belt, thick limestones interbedded with ribbon quartzites, shales and greenstones (together up to 20,000 ft.) and much intruded by Mesozoic granites (LORD, HAGE and STEWART, 1947) have suggested to some (KAY, 1951) that eugeosynclinal conditions existed there, with volcanic island

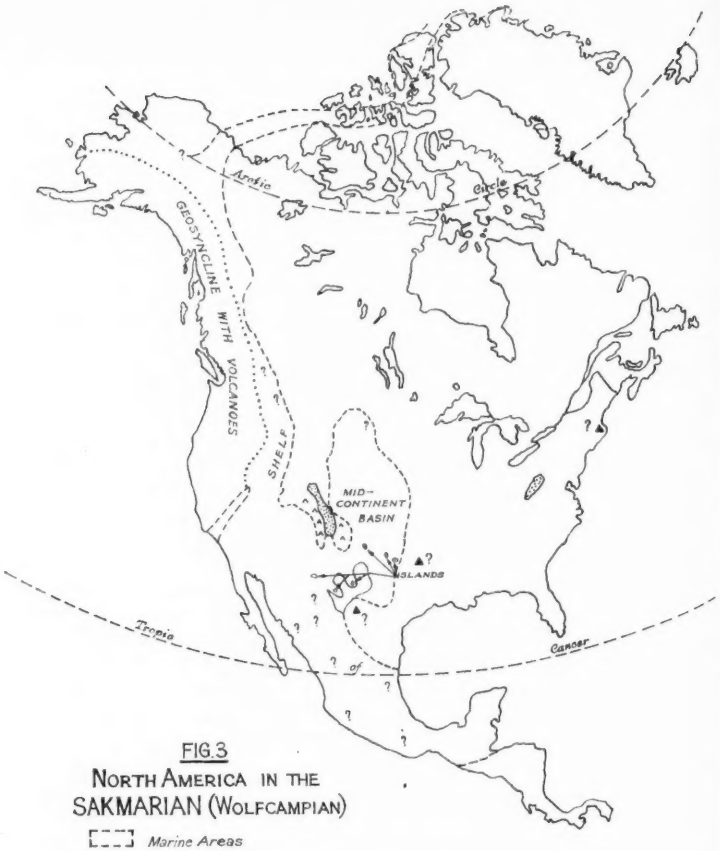


FIG. 3
NORTH AMERICA IN THE SAKMARIAN (WOLFCAMPIAN)

arcs. The deposits (Cache Creek Group and correlatives) contain fusulines and brachiopods somewhat rarely, some probably Sakmarian (THOMPSON, WHEELER and HAZZARD, 1946; MOFFITT, 1954; ROOTS, 1954). The greenstones listed by WHEELER (1940) as Permian seem to be post-Sakmarian (BLACKSTONE, 1954). Coral or other reefs are not recorded. The inner belt contains thinner sediments interpreted as shelf sediments lacking volcanics; one of the best sections is probably that south of the Yukon River in Alaska, where the Tahkandit Limestone, with conglomerates, sandstones

and shale, is abundantly fossiliferous (SMITH, 1939; MCLEARN and KINDLE, 1950).

Possibly half the present warm temperate and subtropical U.S.A. was under the sea during the Wolfcampian Sakmarian; the Pacific eugeosynclinal belt of deposits of late Palaeozoic age stretches down from Canada (KAY, 1951) to Baja California which may have been land, and into Mexico, where connection with the Atlantic may have occurred. The boundary between eugeosyncline and shelf regions ran through Idaho and central Nevada. On the shelf the sea transgressed as far the western boundary of Wyoming and the centre of Utah, then through the S.W. corner of Colorado along coastal flats at the foot of a high range the Uncomprahgee High; thence back north again round a similar high range the Front Range, through eastern Colorado, Wyoming and Montana into N. Dakota, its northmost point in the Sakmarian. The shore line then returned south through easternmost Nebraska, eastern Kansas and Oklahoma, central Texas, where high ranges (the Wichita and Marathon Ranges) fronted it, and thence swung sharply S.E. back into North Eastern Mexico. The shelf appears to have been continuous into the Sonora District of Mexico. This great epicontinental sea was thus constricted by land in Colorado, Wyoming and Montana, with high ranges and an intervening valley in Colorado.

Parts of the floor of this epicontental sea were depressed more than others, and great thicknesses of sediment were deposited for instance in the Oquirrh Basin of S.W. Utah and S.E. Nevada. Sakmarian sediments show the same range in facies throughout these seas. Near-shore, red, green and grey sandstones, shales, sometimes with anhydrite, and salt beds predominate; further from shore limestones formed. No coral reefs are known, but some small structures may be algal-bryozoan reefs. The limestones are often rich in fusulines, and these with ammonoids give the time scale for the Wolfcampian. Knowledge of the extent of the different lithological formations is far advanced in the U.S.A. and in most states is well ahead of the palaeontological knowledge necessary to give the time planes. Advances and retreats of the limestone facies towards and from the nuclear land areas seem to indicate oscillations of sea level, by which the sea advanced and retreated across wide coastal flats at the feet of the ranges [1]).

The absence of coal seams from the coastal plains of the Sakmarian

[1]) The following literature should be consulted for the names and descriptions, faunas and bibliographies of Wolfcampian formations in the various states. Idaho, W. Montana and N. E. Nevada: BLACKSTONE (1954), CRESSMAN (1955), MCKELVEY, SWANSON and SHELDON (1953), NOLAN (1943) and THOMPSON (1954). Utah: BAKER, HUDDLE and KENNEY (1949), EARDLEY (1951), NEWELL (1948), OGDEN, 1951, B.A.A.P.G. p. 62, THOMPSON, WHEELER and HAZZARD (1946). E. Nevada and S. California: MCNAIR (1951), NOLAN (1943), T. W. and H. (1946). Colorado: BAKER and WILLIAMS (1940), BRILL (1952), LOVERING and GODDARD (1950), MAHER (1954), WENGERD and STRICKLAND (1954). Arizona, New Mexico, Texas and Oklahoma: EARDLEY (1951), HILLS (1942), KING (1948), LLOYD (1949), MCKEE (1951), THOMPSON (1954), T. W. and H. (1946). Kansas and Nebraska: MOORE et al. (1951), THOMPSON (1954). Wyoming: AGATSON (1954), WANLESS et al. (1955). N. Dakota: MCCABE (1954).

shelf seas in the western half of the U.S.A. together with the red colour of much of the sandstone and shales, the occasional beds of anhydrite, and the absence of coral reefs, seems to indicate warm temperate regions with seasonal rainfall.

The only deposits in the U.S.A. which might conceivably have been regarded as Upper Palaeozoic glacials are at present discredited as such. Thus the Sqantum Tillite near Boston is regarded as probably Devonian (EARDLEY, 1951), and the "tillites" in the Wichita and Marathon Mountains as piedmont conglomerates with slickensides induced by differential movement (DUNBAR, 1924).

Wolfcampian fusuline genera identified by THOMPSON (1954) are *Boultonia, Dunbarinella, Nankinella, Oketaella, Ozawainella?, Paraschwagerina, Pseudofusulina, Pseudofusulinella, Pseudoschwagerina, Schubertella, Schwagerina* (numerous species) and *Triticites.*

Wolfcampian nautiloid genera identified by MILLER and YOUNGQUIST (1949) are *Bitaunioceras, Coelogastrioceras, Domatoceras, Endolobus, Ephippioceras, Foordiceras, Knightoceras, Liroceras, Metacoceras, Mooreoceras, Pseudorthoceras, Solenocheilus, Stearoceras, Stenopoceras, Tainoceras* and *Temnocheilus.*

Wolfcampian ammonoid genera mentioned by MILLER and YOUNGQUIST (1949) are *Agathiceras, Artinskia, Daraelites, Marathonites* (and *Peritrochia*), *Medlicottia, Metalegoceras, Neopronorites, Paragastrioceras, Properrinites, Prothalassoceras, Pseudogastrioceras.*

Wolfcampian coral genera are *Heritschia, "Lithostrotionella", Lophamplexus, Lophophyllidium, Malonophyllum, "Palaeosmilia"* and *Sochkinophyllum.* Total ranges of the genera named are not indicated in these lists, and the lists are not exhaustive.

In the eastern United States, no marine Sakmarian seas occurred; there were probably high mountains in the Appalachian region (KING, 1951; EARDLEY, 1951); but inland areas of sedimentation were restricted compared with those of Pennsylvanian time. The only deposits reasonably to be attributed to Rotliegende time are those upper parts of the Dunkard Fm. in Pennsylvania, Ohio and West Virginia (JONGMANS, 1952). Here repeated sequences of strata occur ("cyclothems") as in the Pennsylvanian, including coal seams. The shales are mostly grey, but when calcareous may be greenish-grey and greyish-purple to purplish red (CROSS and ARKLE, 1952). The flora is European in type. This seems to indicate a humid climate for the eastern U.S.A. with persistent, rather than markedly seasonal rainfall. When contrasted with the lack of coals in the Western shelf basins, it would seem to indicate that U.S.A. was in a region of dominantly easterly winds.

In Mexico and tropical Central America Upper Palaeozoic seaways are hard to interpret, owing to our small knowledge of the few exposures. Mexico could indeed have been almost entirely submarine, an exception being that part along the border with S. Texas, where mountains must have existed to supply the coarse sediment along the margins of the basins. In S.W. Coahuila the lowest exposed upper Palaeozoic beds are

greenish black greywackes with possibly some lava, and fine grained quartzite, overlain by blue grey, extremely massive crinoidal limestone, possibly in part reef, though evidently not coral reef. These are probably Pennsylvanian or possibly Wolfcampian. Unfossiliferous clastics with layers of coarse conglomerate, shale, and thin layers of sandstones and greywackes were thought to be tillites by Kelly, but this view has been discredited by King, Dunbar, Preston Cloud and Miller (1944). This sea was continuous with the Texas seas, and opened into the Gulf of Mexico. It may also have been continuous with the seas of Sonora, in the N.W. of Mexico.

In the extreme S.E. of Mexico (Chiapas) and running through Guatemala E—W and into British Honduras are marine clastics, followed by Wolfcampian (Grupera Fm. 400 ft) and Leonardian shales and limestones with fusulines (Sapper, 1937; Schuchert, 1935; Mullerried, Miller and Furnish, 1941; Thompson and Miller, 1944). How this sea was related to that of Coahuila and that of Sonora is unknown; its fossils indicate relation with those of Texas.

In the Sonora seas, massive limestones, some reefy, graded laterally into thin-bedded, dark granular limestones with abundant crinoidal fragments and fusulines; Wolfcamp may be present, Leonard and Word certainly are; the limestones are continuous with those of S. Arizona (Imlay, 1939; King, 1939; Dunbar, 1939).

South America

Wolfcampian (Sakmarian) faunas have been identified with reasonable certainty only in a narrow belt in the Andes, stretching from Cochabamba (S. of L. Titicaca) in Bolivia through Peru and doubtfully into Equador (Newell, Chronic and Roberts, 1953). The strata containing them are black, bituminous shales and massive limestones with some dolomite, sandstone and siltstone and are referred to the Copacabana group which lies unconformably on the Devonian near L. Titicaca and is overlain unconformably by the clastic and volcanic Permian Mitu group. The faunas consist chiefly of brachiopods, mollusca and fusulinids (Kozlowski, 1914; Newell, Chronic and Roberts, 1953) and are like those of N. America, with *Juresania* and *Kiangsiella*, and unlike those of Australia. They possibly continue through Colombia (Gerth and Kräusel, 1931) into the Maracaibo region of Venezuela (Thompson and Miller, 1949), where some fusulines and cephalopods may be Wolfcampian, others Leonardian. In the Amotape Mountains and Tarma region of Peru, a mid-Pennsylvanian fauna unknown in Bolivia occurs (Newell, Chronic and Roberts, 1953).

This mid-Pennsylvanian fauna has been recognised in several places between 60° and 50° W. in a seaway which stretched along the Amazon in Palaeozoic times, in shale referred to the Itaituba Series (Caster and Dresser, 1954; Mendes, 1957), and in the R. Parnohyba basin (about 43° W) in the Piaui Series (Kegel, 1953). Whether this seaway lasted into Wolfcampian times is unproved, but from Kegel's work it would seem to have withdrawn at least from the Parnohyba region by then.

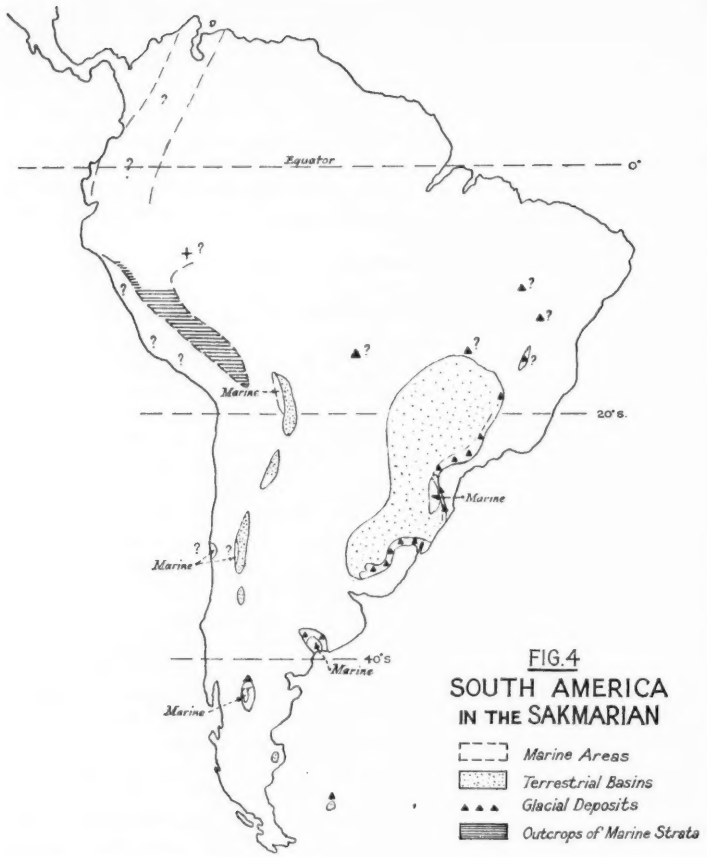


FIG.4
SOUTH AMERICA
IN THE SAKMARIAN

Whether the Peruvian Sakmarian sea, which NEWELL, CHRONIC and ROBERTS (1953) regarded as transgressing from the west, extended south along the Andes into Chile and the Argentine is uncertain. Marine strata in the R. Chiapa valley in Chile have a small brachiopod and molluscan fauna generally regarded as either Gshelian (Orenburgian) or Sakmarian (FOSSA-MANCINI, 1944) as is the neighbouring fauna from the Argentinian precordillera at Barreal (REED, 1927) though CASTER (1954) advocates an equation to the Pennsylvanian Itaituba fauna of the Amazon and the Tarma fauna of Peru. Precise faunal studies are required. These faunas are very important, for in the Argentinian pre-Cordillera there are florules which FRENGUELLI (1944, 1946) interprets as indicating the gradual replacement of the cosmopolitan *Rhacopteris* flora by the *Glossopteris* flora.

The sections, like those with the marine faunas, are discontinuous in the field, and there is only indirect evidence on sequences. FRENGUELLI deduces the El Saltito flora (*Rhacopteris* and *Lepidodendron*) to be lower Westphalian; that of La Playita (similar but without *Rhacopteris* itself and with *Gondwanidium plantianum*, the earliest representatives of the *Glossopteris* flora) upper Westphalian, that of Retamito (in varves) lower Stephanian, and that of Bayo de Velis, which is almost a pure *Glossopteris* flora although the early *Gondwanidium* is still present, upper Stephanian. He prefers to draw the base of the Permian (presumably, to him, basal Rotliegende) above the last appearance of *Gondwanidium*, though BARBOSA (1952) draws it below the base of the Bayo de Velis Fm., both positions of course, being arbitrary.

Glacial deposits such as tillites, fluvio-glacial conglomerates and varves, are found interbedded in these discontinuous pre-Cordilleran sections (HEIM, 1945) and their number and relation to floras and faunas can only be deduced indirectly. At present we can say no more than that the "*Spirifer supramosquensis*" beds of Barreal may be Sakmarian, or possibly Pennsylvanian; the plant beds of Bayo de Velis and of Totoral may be Rotliegende or Pennsylvanian. Two sets of supposed glacials at least, that below the *Rhacopteris* flora of el Tupe, and that of Retamito are pre-Sakmarian. BARBOSA (1952) considers that in the Bayo de Velis, the red Pataquia and the Totoral formations, the only glacial material is that derived from the erosion of the earlier tillites and fluvioglacials. Clearly we can as yet draw no safe palaeogeographic and palaeoclimatic picture of the Sakmarian of this region.

Further south, in Patagonia at about 43° S in the Sierra de Tepuel etc., the Tepuel system of black shales and quartz sandstones contains in its upper parts *Eoasianites* and *Anthracoceras* referred to the Mid-Pennsylvanian (MILLER & GARNER, 1953) and *Strophalosia, Mourlonia, Aviculopecten* and *Spirifer* cf. *octoplicata* (SUERO, 1952) suggesting by their names Australian Permo-Carboniferous faunas. The lower Tepuel system contains *Fenestella* and *Productus* in glacio-marines. Relation to the Barreal faunas is uncertain, as is the Sakmarian palaeogeography and climatology of the region.

East of this narrow Andean zone where upper Palaeozoic marine strata may be found there is in the sub-Andes of Bolivia (AHLFELD, 1946) and north west Argentina (BARBOSA, 1952) an unfossiliferous "Gondwana" development of continental rocks, generally called Oquita group in their lower parts, (with greyish sandstones and shales, tillites and fluvioglacials) but followed by the red Mandiyuti Formation, in which primary glacials are probably absent. Some part of this continental sequence may be Sakmarian.

In the remainder of S. America, upper Palaeozoic strata that may contain Sakmarian equivalents were deposited in N.E. Argentina and in the great inland Parana Basin, which stretches over south eastern Brazil, eastern Paraguay, into Uruguay, and possibly into the Diamantina area of Matto Grosso, S.W. Brazil.

Throughout the Parana basin, there is an important marker formation, the Irati or White Band, of black shales and white dolomites with concretions and beds of chert, and containing bones of the reptile *Mesosaurus*, seemingly deposited in the basin when it stood low enough to be invaded by the sea. Below the Irati the beds contain important glacials and are grouped as the Tubarao Formation. BEURLEN (1957) contrasts the absence of evidence of glacial and interglacial erosion in these deposits with its presence in the European Pleistocene glaciation, and concludes that the ice advanced north into a subsiding Parana Basin and south into N.E. Argentina from a high shield region in Rio Grande do Sul. MAACK (1957) considers the ice advanced South, South west and West into Brazil, Uruguay and Argentina from one centre in North east Brazil and others outside the continent. The Tubarao varies greatly in facies along and across the Basin. Thus five tillites (with interbedded coal seams) are recognised in the east in Sao Paulo, 4 in the south of Parana, 2 or 3 in Santa Catarina and only 1 in Rio Grande do Sul. In the north and west (Minas Geraes and Matto Grosso) possibly two or three tillites occur (ALMEIDA, 1952; BEURLEN, 1956). Coals are best developed in the central east and south between the tillites. PUTZER (1957) has discussed the palaeogeographic relationship of these coals and interprets them as formed in a tundra-like milieu, in interstadials or post glacial times; this would suggest the *Glossopteris* flora was a cold-temperate flora. Perhaps detailed studies on the coals would show whether their vegetable matter altered in the manner of modern cold-temperate peats. On the north and west, the beds are red. In this dominantly continental development, marine beds occur along the eastern outcrop, and principally in Santa Catarina and Parana (MENDES, 1952), the oldest at Capivari in Sao Paulo, the most widespread in Parana, Santa Catarina and Rio Grande do Sul. None of them permit any secure correlation with either Pennsylvanian or Wolfcampian faunas of America, and one, that of Taio (Santa Catarina) has a lamellibranch fauna with some genera known in Australia, though lacking *Eurydesma*. According to BARBOSA (1952), NEWELL (1949) saw correlation between the Capivari and the Sakmarian of Peru, while according to CASTER (1952) this is a depauperate representative of the Pennsylvanian of the Amazon. No *Rhacopteris* occurs in the Tubarão, but *Gondwanidium* is recorded (DOLIANTE, 1952) moderately high in the series, suggestive, perhaps, of a Bayo de Velis correlation for the Tubarão.

Above the Irati follows the Passa Dois Series, also of variable but mainly continental facies, without glacials except possibly for varves in the Theresina member; in the north and west it is developed in red facies. A marine or brackish band with the lamellibranchs *Pinzonella* previously regarded as Triassic is now referred to the Permian (MENDES, 1952).

It is thus clear that only subjective views are available or possible on the ages of the various strata of the Parana Upper Palaeozoic, and it is impossible to draw a secure Sakmarian map. If the Tubarao is Sakmarian, glaciated mountains probably existed to the east of South east Brazil; the sea also lay to the east, and spread westwards into the Basin, possibly

through an opening in the ranges east of Santa Catarina. If the Irati is Sakmarian, the ranges to the east were not glaciated at that time; if the Passa Dois is Sakmarian, likewise, glaciation to the east may have been absent.

In the mountains to the south of Buenos Aires in Argentina, the Pillahuinco Group has the Sauce Grande Formation, 900 metres of tillite and glacial conglomerates with massive quartzites at the base which many correlate with the Tubarao Formation of Brazil. Some distance higher occurs the Bonete Formation of dark green marine quartzites and mudstones with 3 fossiliferous beds; the total fauna is very Australian in type, with *Eurydesma*, *?Atomodesma* (= *Aphanaia*), *?Stutchburia*, *Allorisma*, *Schizodus*, *Promytilus* and *?Liopteria*, and the brachiopods *Notospirifer darwini* and *"Chonetes"* (HARRINGTON, 1955). On the known ranges of these genera, it could be Sakmarian but it could be younger. The flora of the Bonete is a pure *Glossopteris* flora, no *Gondwanidium*, or any relics of the *Rhacopteris* flora being present, and FRENGUELLI (1944) considered it younger than the U. Stephanian Bayo de Velis flora.

None of the invertebrate species of the Bonete Formation are found in any of the Tubarão faunas, and the Irati White band is unknown in the Sierra Bonaeres. Whether the glacial deposits of both areas should be correlated as contemporaneous is arguable; 5 glacial stages have been recognised in some parts of the Parana Basin, only 1 in others; the number of stages in the Sauce Grande Formation is unknown to me.

It must be concluded, I think, that evidence by which we could safely correlate any section of the Parana or Pillahuinco or Barreal faunas with the Wolfcampian of America is lacking; should it become available, then we would have a means of dating (in terms of the Northern Hemisphere sequences) the development of the *Glossopteris* flora in South America. Failing any reasonable marine correlations, we might perhaps use the floral correlations of FRENGUELLI (1944, 1946), who appears to regard the Bonete flora as Rotliegende; the Rotliegende is reasonably correlated with the Sakmarian and this would suggest a Sakmarian equivalence for the Bonete Formation. Whether the Sauce Grande glacials below it would be Wolfcampian or Pennsylvanian would still be uncertain and arguable. Whether the Tubarão floras of the Parana Basin would be equivalent to or older than the Bonete floras is arguable; since *Gondwanidium* is still present, it might be suggested that they are pre-Bonete. It is clear then, that we have no reasonable palaeontological evidence on the precise age of the Tubarão or the Sauce Grande glaciations. We might observe that the *Eurydesma* fauna entered after the Sauce Grande glaciation had disappeared.

In the Falkland Islands, continental glacial deposits followed by beds with *Glossopteris* are known; and in two small areas it is suggested that marine glacials are present (ADIE, 1952). There is no evidence to show whether any of these deposits could be contemporaneous with the Sakmarian marine beds of Europe. SUERO and ROQUE (1955) have shown that the Falkland Is. beds may be related to those of Bahia Laura and the

Sierra de Tepuel, so that there is no longer any need to drift them up towards Brazil to make them "fit", as DU TOIT did.

Table 3. Approximate correlation of S. African standard sequence with eastern S. American sequences.

	S. Africa and S. W. Africa	S. America Parana Basin	S. America
?Artinskian	Upper Ecca Shales		
?Sakmarian	Lower Ecca Shales White Band Boulder mudstones with *Eurydesma* Dwyka Tillite	Irati White Band Tubarão Fm. with glacials	Bonete Fm. with *Eurydesma* Sauce Grande glacials.

Africa

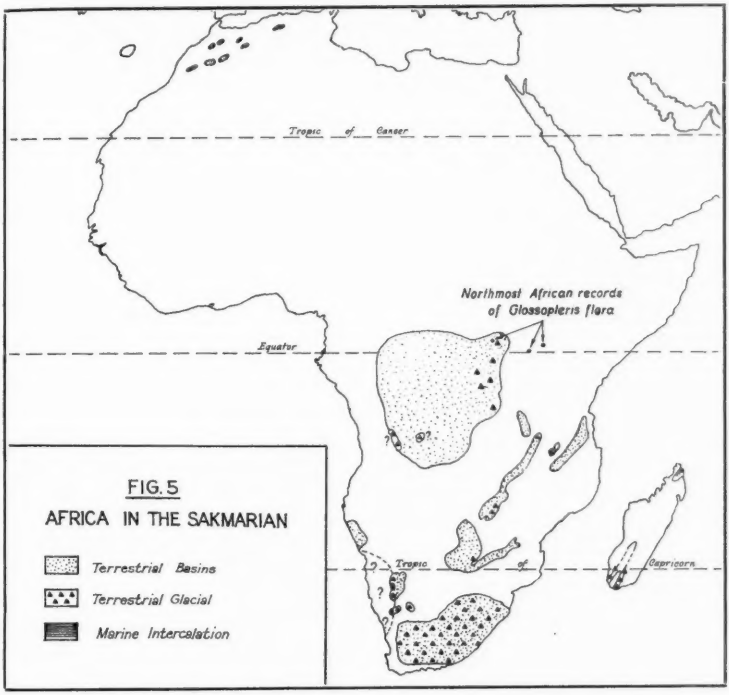
No marine beds with the fusulines, goniatites and brachiopods regarded as characteristic of the European Sakmarian or its North American equivalent, the Wolfcampian, have been found anywhere in Africa. Africa indeed, was almost entirely continental during the upper Palaeozoic, short and narrow marine transgressions being known only in South West Africa and in Madagascar. It is impossible to say as yet, which of the African deposits if any, are Sakmarian equivalents, so that views on the Sakmarian palaeogeography are not of much value.

In the North, in Morocco, Algeria and Tunis the only deposits found are intramontane continental deposits with some coals, the flora being that of the Autunian or Rotliegende of the Euramerican province. In Egypt, Sudan, the Sahara, Upper Guinea and French Equatorial Africa no deposits which could possibly be referred to Sakmarian times are known, and it could be that the region was a desert at the time, receiving insufficient precipitation for transport of sediment.

South of the equator, continental deposits are widespread, being formed between late Carboniferous and Jurassic times, and constituting the Karroo System. In the main part of the Karroo Basin in the Cape Province, Orange Free State and Natal, which might be regarded as standard, the sequence requiring consideration for the recognition of Sakmarian equivalents is, at the top, the Beaufort Beds, then the Ecca Shales, then the Upper Dwyka Shales with the White (*Mesosaurus*) Band near its top, and, at the base, the Dwyka Tillite.

The shales under the Tillite, formerly called the Lower Dwyka Shales, are now known to be disconformable with the tillite and have been transferred to the Witteberg Series (HAUGHTON et.al., 1953). The Dwyka Tillite attains its maximum thickness in the belt of country north of the northernmost Witteberg outcrop, where it has an average thickness of 2,000 feet. It thins again further north. The surface on which it lies was in general

one of pronounced relief, with fairly deep, approximately north-south valleys running between ranges, the tillites being preserved within the valleys, but absent or very thin on the bounding heights. Much of the material for the southern facies of the tillite appears to have been derived from a (now vanished?) land mass lying to the south (HAUGHTON, 1952). North of latitude 28° the tillite is almost completely absent, the Ecca beds



resting directly on the basement, due, according to ROGERS et. al. (1929) and MACGREGOR (1947), to its having been removed by pre-Ecca erosion.

In places, isolated developments of coarse sediments at the base of the Karroo sequence, particularly in the rift valleys, have been identified as glacials; these are in Bechuanaland (GREEN and POLDERVAART, 1954), Southern Rhodesia (BOND, 1953) Tanganyika (HARKIN, MCKINLEY and SPENCE, 1954), Belgian Congo (Lower Lukugu Series, CAHEN, 1954) and Angola (MOUTA and CAHEN, 1951). The nature of these glacial deposits in S. Rhodesia and Belgian Congo suggests to BOND and to CAHEN that they were deposited by valley glaciers rather than by a continental ice sheet. But MACGREGOR (1947) in accordance with DU TOIT's view that the striated

pavements of the Karroo indicated S. Rhodesia as a centre from which flowed the ice that formed the great boulder beds in the Union, suggested that the ice here may have formed a stationary conical core from which upper layers slid outwards in all directions, and that such glacial deposits as were formed were probably thin and had been mostly washed away before the Wankie coal measures were formed.

South West Africa too has a dissected pre-Dwyka surface, and the tillite is thickest in the pre-Dwyka valleys (MARTIN, 1954) at least one of which, the Kunene, has a "U" shape inherited from the Dwyka ice. MARTIN (1950) considered the glacials of S.W. Africa spread out from two high regions, lying N and S of the Damara.

It seems probable that valley glaciers and possibly mountain ice caps formed on the highlands surrounding separate basins of deposition in the area S. of the Equator, and that the continental ice, if in fact such existed, was developed as a continuous sheet only in the Karroo Basin. DU TOIT's interpretation of much of the higher Dwyka Tillite of the southern outcrop of the Union as water-laid material on low land may be accepted, but flooding by the sea seems to have been confined to the western edge only, in the south of S.W. Africa only; there may have been highlands to the south, along the Palaeozoic folded belt of the Union.

Our safest line of evidence in correlating the African glacials is the marine fauna of South West Africa. However, apart from the fishes, this is a *Eurydesma*, i.e. a Gondwana fauna; the fishes give no better indication of age, according to GÜRICH (1923) than end of the Carboniferous — beginning of the Dyas.

According to MARTIN (1954) the *Eurydesma* fauna occurs in the marine-glacial boulder mudstone that follows the dark-grey or black bituminous shale with the Ganikobis fish fauna, which itself lies directly above the basal continental ground moraine. Marine glacials follow above the *Eurydesma* boulder mudstone, so that in S.W. Africa we have proof that the *Eurydesma* fauna was a cold-water, near-shore fauna, glacier ice dropping boulders into the deposits in which the *Eurydesma* shells are found.

These boulder-mudstones pass upwards into the Upper Dwyka shales, whose upper parts are white weathering and contain the White (*Mesosaurus*) Band, a remarkably constant development of the Karroo and the southern part of S.W. Africa, post glacial, and evidently deposited in a low lying coastal or estuarine region. Conditions and fauna were closely similar to those of the Irati White Band of S. America, and although the species of *Mesosaurus* are distinct, no great difference in age would seem to be apparent between the two. Unfortunately there is no reasonably safe correlation of either White Band with the European or North American succession, since *Mesosaurus* is confined to S. Africa and S. America and its relationships are obscure. Von HUENE (1940) correlates the S. African Band with the basal Rotliegende which would be Sakmarian, and the S. American with the later Rotliegende, which might be Artinskian.

The Ecca Series, entirely continental, and non-glacial, consists of bluish

and greenish shales, sandstones and some coal seams, seemingly of drift origin. They transgress across the Dwyka on to older rocks, but in the Karroo Basin are thickest and coarsest in the South (HAUGHTON, 1952). *Glossopteris, Schizoneura* and *Phyllotheca* are recorded from their southern outcrops, and in the Middle Ecca Shales the *Glossopteris* flora is apparently intermingled with northern or relict forms such as *Sigillaria, Bothrodendron, Lepidodendron* and *Psygmophyllum* (ROGERS et.al., 1929).

The Beaufort beds which follow are continental sandstones and shales, rich in vertebrate fossils, chiefly reptilian. The Beaufort beds have been divided into 6 zones on the reptilian fossil assemblages; three in the lower, one in the middle and two in the upper beds. The three lower Beaufort Zones are correlated with zones II, III and IV of the Russian reptilian sequence by VON HUENE (1940), i.e. with Kazanian and Tatarian horizons, much younger than Sakmarian. HAUGHTON (1953) also equates the L. Beaufort zones with II, III and IV of Russia, but shows that similarity is great only between Zone III of S. Africa and Zone IV of Russia. EFREMOV and VJUSCHKOV (1955) equate the lowest S. African reptilian fauna of the Beaufort Beds with the upper Kazanian. If the reptile authorities are right, then the Beaufort beds are wholly younger than Kungurian.

Fresh-water mollusca (*Carbonicola, Kidodia, Palaeoanodonta,* and *Palaeomutela*), (HAUGHTON et. a., 1953) support the reptilian age determinations for the Lower Beaufort Beds, following determinations by COX (1936) of fresh water mollusca from Lower Beaufort and Ecca or L. Beaufort correlatives in Tanganyika.

North of the main Karroo Basin, older Karroo strata are non-marine and in general have considerable thickness only in rift valleys (GREEN and POLDERVAART, 1954; BRANDT, 1954). They are of smaller extent than and are overstepped by the Mesozoic upper Karroo beds, thus possibly indicating the existence of ancestral rift-valleys in pre-Karroo times. The basal beds, exposed in isolated areas, may be coarse or conglomeratic; some of these, in Bechuanaland (GREEN and POLDERVAART, 1954), Southern Rhodesia (BOND, 1953), Tanganyika (HARKIN, MCKINLAY and SPENCE, 1954), Belgian Congo (CAHEN, 1954) and Angola (MOUTA and CAHEN, 1951) have been recognised as glacial and correlated with the Dwyka. But in many places, in Northern Rhodesia (BRANDT, 1954), Mozambique (BORGES, 1952), Nyasaland (DIXEY and WILLBOURN, 1951), Portuguese Nyasa (BORGES, NUNES and FREITAS, 1954), Kenya (TEMPERLEY, 1952) and Uganda (DAVIES, 1952), no glacials have been recognised and the basal beds are correlated with the base of the Wankie Series of sandstones, shales and coals seams of S. Rhodesia, which Series is itself correlated with the Ecca. The Wankie Coals are mainly drift coals (BOND, 1952). The isolated glacial deposits in these northern states would appear to be from valley glaciers rather than from any extensive ice sheets. The sources of the sediments correlated with the Ecca Series would seem to be from the highlands immediately surrounding the separate basins of deposition.

Plant fossils are practically the only direct source for an age determination of the Dwyka and Ecca correlatives in the north. Thus TEIXEIRA

(1951) records *Neuropteridium* (*Gondwanidium*) *validum* and *Noeggerathiopsis* from the formation with glacials in Angola. CAHEN (1954) lists *Cyclodendron, Voltzia, Cyclopteris, Artesia, ? Ullmannia, Gangamopteris, Noeggerathiopsis* and *Phyllotheca* from the Lower Lukuga Series of Belgian Congo.

The Upper Wankie sandstones of S. Rhodesia contain *Glossopteris, Gangamopteris, Noeggerathiopsis* (as *Cordaites*), *Cladophlebis*, and *Sphenopteris* and the Euramerican *Sphenophyllum, Pecopteris, Chansitheca* and cf. *Cyclodendron* (BOND, 1952). This flora was considered correlatable with the Rotliegende (i.e. Sakmarian) or older by WALTON (1929). But JONGMANS (1952) considers it upper Stephanian, i.e. still within the Pennsylvanian.

The beds at Tete in Mozambique, correlated with the Upper Wankie, contain a similar assemblage and are considered "L. Permian" by TEIXEIRA (1951).

In Uganda, at Entebbe, the most northerly occurrence of the *Glossopteris* flora, Euramerican forms are present also (DAVIES, 1952). On the evidence of spores from coal seams in Natal, RILETT (1955) considers the Middle Ecca coals to be not later than Artinskian.

Thus in many of these presumably pre-Beaufort i.e. pre-Kazanian beds, *Glossopteris* and Euramerican floras are admixed. Botanists regard the Ecca-Wankie floras variously as upper Stephanian or Rotliegende.

We thus have as yet no firm basis for concluding whether Sakmarian correlatives are present in S. Africa, or if so, which they are.

BOND (1952) considers the climate in Rhodesia, during Dwyka and Ecca times to have been wet. CAHEN (1954) considers the Belgian Congo climate to have been cold and humid in Lower Lukugu times, and humid and less cold in upper Lukugu times.

In Madagascar, BESAIRIE (1952) shows that the Sakoa Group outcropping in a limited area in the south, has black shales and tillites at the base, which are quite analogous with the Dwyka of S. Africa, followed by beds with coal containing a pure *Glossopteris*' flora, red beds with silicified wood, and at the top a marine transgression with *Productus, Spirifer* and lamellibranchs. These offer a prospect of future correlation with European marine sequences. The Sakamena group is transgressive and discordant on the Sakoa Group, and is essentially shaley and continental in facies, with some marine intercalations, the lowest of which contains the alga *Anthracoporella,* and the lamellibranchs *Gervillea* and *Modiolopsis* in species which are known in lower Beaufort equivalents in Tanganyika. Higher beds contain a *Glossopteris-Thinnfeldia* flora, and reptiles regarded as Beaufort equivalents. In the North of the Island (Ankitokazo) beds with *Productus* and *Spirifer* contain a fauna quite distinct from the beds with *Productus* and *Spirifer* in the south (Vohitolia) (ASTRE, 1934). The northern *Productus* fauna contains *Xenaspis carbonarius* of the Upper Permian; but whether the southern *Productus* fauna is of similar age, as BESAIRIE concludes, is questionable and deserves further study.

In the map of Africa offered, I have made the not really justifiable assumption that the Dwyka tillites and shales and Lower Ecca Shales are Sakmarian.

Antarctica

No Sakmarian strata can be safely identified in Antartica, and no marine beds are known in outcrop. The continental Beacon Sandstone, a horizontal mass at least 1,500 feet thick, developed in Victoria Land and possibly under the Ross Sea (Adie, 1952), may however contain Sakmarian equivalents. *Glossopteris* and *Vertebraria* have been collected from calcareous sandstones, siliceous shales and coaly beds on Mt. Buckley nunatak that projects through the Beardmore Glacier, presumably high in the Beacon formation, which outcrops along the western shore of the Ross Sea and along both sides of the Beardmore Glacier (Seward, 1914); Upper Devonian fish scales are known from the moraine at the foot of Mt. Suess. Slabs of Beacon sandstone show ripple marks and sun cracks and the inference from the combined lithological and palaeontological evidence is that continental strata were deposited in this region continuously from the Upper Devonian to the Permian, including the Sakmarian. No tillites or varves have been reported from within the Beacon sandstone, but it does not seem reasonable to infer from this that upper Palaeozoic glaciation did not occur in Antarctica. We still know far too little about that continent.

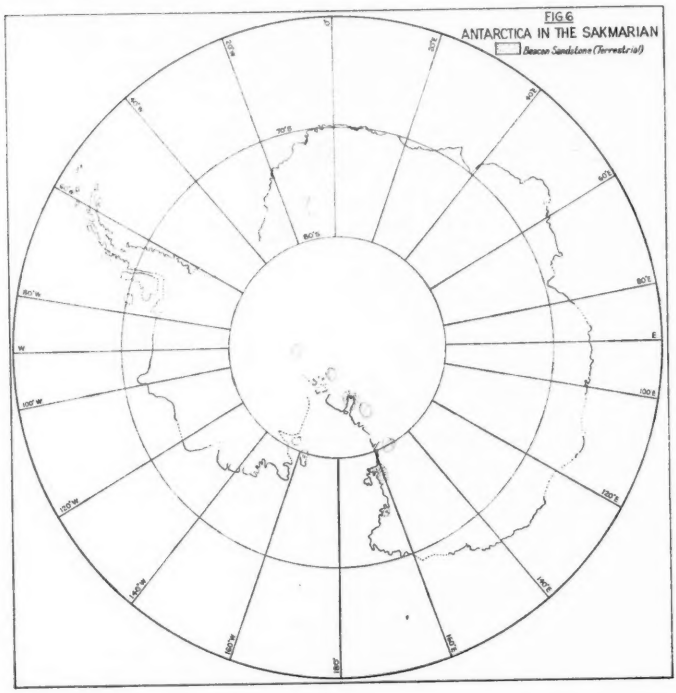
Australia

Of the "Gondwanaland" countries, Australia appears to have the earliest Gondwana marine faunas; but since its characteristic Gondwana elements are unknown in the northern hemisphere (except in the Salt Range), and since there are few goniatites and corals and no fusulines, the recognition of Sakmarian horizons is difficult. There is however considerable agreement amongst Australian geologists on the position of the boundary between the Sakmarian and Artinskian Stages, as evidenced in the A.N.Z.A.A.S. symposium reviewed by Hill (1955).

The eastern Australian Permian fauna has fewer similarities to the N. Hemisphere fauna than the western Australian, and it is to the west that we look for our best chance of intercontinental correlation, leaving the eastern faunas to be correlated via the western.

In the Symposium mentioned above, it was agreed that in Western Australia the boundary between Sakmarian and Artinskian might fall at the base of the marine Nura Nura member with *Metalegoceras* and *Thalassoceras* in the Fitzroy Basin, at the base of the Callytharra formation in the Carnarvon Basin, and at the base of the Fossil Cliff beds in the Irwin R. Basin. *Metalegoceras* and *Uraloceras* occur in a marine intercalation in the Holmwood Shale above the Nangetty glacials; these two are not known before the Upper or Sakmarian substage of the Sakmarian stage in the Urals. If the boundary lies at the base of the Nura Nura Member, part or all of the Grant Sandstones with glacials in the Fitzroy

Basin, the Lyons (?marine) with glacials in the Carnarvon Basin, and the Holmwood Shale and Nangetty continental glacials in the Irwin River Basin are Sakmarian; the W.Australian Sakmarian fauna would then be very poorly known. *Eurydesma* occurs in transitional beds between the Callytharra Fm. and the Lyons Group, and 1,500 feet below the top of the Lyons there is a marine fauna with productids and spiriferids that THOMAS (1954) con-



siders a local representative of the Umaria fauna of India, which however is not as yet safely correlated with the Ural sequence; these productids are not known in eastern Australia. As a result of the above, marine glacials are shown in the map of Australia in the Carnarvon, Fitzroy and Bonaparte Gulf Basins, and terrestrial glacials (probably Alpine type) in the Irwin River, Collie and Wilga Basins, and the Canning Desert Shelf.

Recently however RUZHENTSEV (1956, p. 143) has placed the W. Australian species *Metalegoceras clarkei* MILLER from the Nura Nura Member in the synonymy of *M. tschernychewi* (KARPINSKY) which in Russia enters in and characterises the upper Artinskian. If, for this reason, an upper Artinskian horizon should be preferred for the Nura Nura Member and

equivalents, the top of the Sakmarian might be well down in, or even below the glacials.

Whether or not a continental ice sheet was present in W. Australia in the Sakmarian is yet to be established. Some authors have assumed it, but the evidence seems to me insufficient.

S. Australian upper Palaeozoic glacials are shown by CAMPANA (1954) to be of Alpine type. Victoria also, though possessing land glacials and peri-

FIG.7
AUSTRALIA IN THE SAKMARIAN

Marine Areas
Terrestrial Basins
Glacial Deposits

glacials, seems to me to have had at the most a small mountain ice cap, not a continental sheet. There is no certainty that either the Victorian or S. Australian glacials are coeval with the W. Australian ones, which as seen above we assume at present to be at least in part early Sakmarian. LUDBROOK (1957) has found Permian arenaceous foraminifera in claystones interbedded in the fluvio-glacial sequence in Yorke Peninsula, S. Australia.

In New South Wales the main glaciation (Upper Kuttung) was long pre-Sakmarian, probably Moscovian. But marine glacials are known in the Allandale Fm. of the Lower Marine (Dalwood) Group with a rich but incompletely described *Eurydesma*-"*Aviculopecten*" fauna, and these are generally correlated with the West Australian main glacials; they could indeed be Sakmarian. *Pseudogastrioceras*, in the somewhat younger Farley Formation has been compared with Artinskian species (TEICHERT, 1953).

Table 4. Tentative Placing of the Boundary between Sakmarian and Artinskian in Australia.

	Sakmarian	Artinskian
Carnarvon Basin W. Australia	Lyons Gp. with glacials (*Eurydesma* at top). Umarian productid fauna 1,500 ft. below top	Callytharra Fm.
Irwin R. Basin W. Australia	Holmwood Shales Nangetty glacials	Fossil Cliff Beds
Fitzroy Basin W. Australia	Grant Sandstone with glacials	Nura Nura Member
Tasmania	*Eurydesma* zone over Basal glacials	Grange mudstone and Berriedale limestone
Hunter River, New South Wales	Allandale Fm. with *Eurydesma*	Rutherford Fm.
Bowen Basin, Queensland	Cattle Creek Fm. with *Eurydesma* and marine glacials	Aldebaran Sandstone
Artesian Basin, Queensland	Joe Joe Fm. with terrestrial glacials	Colinlea Fm.

In Tasmania the Basal Glacials and the *Eurydesma* zone just above them may well be Sakmarian, but again we have no serviceable descriptions of the fauna.

In Queensland, HILL (1953) and MAXWELL (1954) have suggested that the Cracow fauna at the base of the marine sequence in the S.E. of the Bowen Basin is Sakmarian; the fauna includes *Taeniothaerus*, *Aulosteges*, *Cancrinella*, *Terrakea*, *Anidanthus*, *Horridonia*, *Strophalosia*, *Lissochonetes*, "*Martiniopsis*" (2 genera), *Neospirifer*, *Trigonotreta*, *Spiriferellina* and several other spiriferoid genera; *Eurydesma*, pectinoids, platychismoids, and many other undescribed forms, but no goniatites or fusulines. Terrestrial glacials with *Glossopteris* that may be coeval form the Joe Joe Formation of the Springsure district; but they could equally be Orenburgian, for all the direct evidence we have. Marine glacials occur in the Cattle Creek Formation of the S.W. exposure of the Bowen Basin, this fauna being thought to be roughly equivalent to the Cracow fauna.

Because of this rather weak evidence, the map of Australia shows marine areas in the south end of the Bowen Basin, with glaciated highlands south of the Springsure region, and marine areas in the Yarrol and Gympie Basins, and in the Northeastern part of New South Wales and in Tasmania. No Sakmarian coals or salt deposits are known. There must have been sufficient precipitation to nourish the glaciers of the West and

the East, and the climate must have been somewhat cooler than the present.

In New Zealand neither Sakmarian faunas nor upper Palaeozoic glacials have been distinguished, and in view of this ignorance it has been left blank on the world map.

Palaeogeography of the Sakmarian

It will have been seen above that our Sakmarian palaeogeographical reconstructions can be reasonably accurate at present only for the continents of the northern hemisphere; difficulties of stratigraphic correlation with and within the continents of the southern hemisphere render these southern reconstructions subject to the bias of individual authors, and I have given the reasons for my preferred correlations above.

The extent of marine areas on the world map (fig. 8) shows that, unless parts of the continents that were exposed during the Sakmarina are now hidden from us under the present sea, the land masses of North America, Eurasia and South America wer considerably reduced by epicontinental and geosynclinal seas, while those of Australia, Antarctica and Africa were relatively very little affected in this way. The decrease in area of land surface in the Northern Hemisphere may have profoundly modified the circulation of the atmosphere and of the oceans, and the changes in circulation may have affected regional temperatures.

The topographic relief of the continents during the Sakmarian is still too difficult to assess, and the height and trends of the Sakmarian ranges are still too problematical for us to deduce their possible effect on the atmospheric circulation and on the belts of precipitation. Both Europe and N. America would seem, judging from the development of coal seams, to have had less precipitation in the Sakmarian than in the Pennsylvanian, and more than in the Kazanian. Heights and positions of plateaus are even more difficult to establish than those of fold mountain ranges.

Biogeographical provinces may give some lead by indicating the positions and perhaps the nature of barriers to the migration of floras and faunas.

What we might call the *Eurydesma* province is separated from what we might call the *Pseudoschwagerina-Pseudofusulina* province by only the width of Tethys to the north of India, by a land barrier in S. America and by Africa, while Australia lay wholly within the *Eurydesma* province; the most likely barrier between these marine provinces seems to be temperature; and the *Eurydesma* fauna does seem to be present where marine glacials are known, or in the marine inundation following land glaciation. Further precision is required, however, particularly in relation to the northward extent of the Sakmarian fusulines.

The *Glossopteris* flora seems present in Gondwanaland everywhere before or with the *Eurydesma* fauna, and in Sakmarian time is not known in the Northern Hemisphere except perhaps along the equator of Africa, and in northern India. The northward barrier may have been a desert in Africa, and may have been Tethys elsewhere. Temperature may also have

played a part. The Angara flora may have been separated by a Ural marine barrier from the European and North American flora.

Humid regions may be recognised from the coals formed in them, and from the glacials resulting from excessive precipitation in a frigid area, whether this was in high latitudes or of high relief in low latitudes.

Coals that appear to have been formed in peat swamps occur in the Dunkard Formation of eastern U.S.A., in the Autunian and Lower Rotliegende in W. Europe, Turkey and N.W. Africa, in the Kuznetsk and other Siberian Basins, and in the Taiyuan of China. It may fairly be deduced that all these areas had a high rainfall, but the coals have not been studied to find whether they were formed as tropical or as cold temperate peats.

In the Southern Hemisphere, coals occur in the Tubarão Series of the Parana Basin of S. America, interbedded with glacials. This region too, if we regard the Tubarão as Sakmarian, must have had high precipitation; perhaps the coals are from cold temperate peats; possibly the winds bringing the moisture were from the Atlantic to the east. Some of the Ecca coals of S. Africa may have been Sakmarian, but they seem to be drift coal.

Aridity, probably intermittent, is suggested by anhydrites etc. in the shallow edges of the mid-continent seas of western U.S.A., and in some of the European continental basins.

Glacial climates. It is still doubtful whether the Dwyka Tillite, the Talchir Boulder Beds, the Tubarão and Sauce Grand Glacials, and the Lyons and Grant glacials are Sakmarian or younger or older, or whether indeed they are all equivalent in age. On the maps offered, however, I have made the assumption that they are Sakmarian as the most reasonable deduction from the present totally inadequate evidence. On this assumption glacial climates appear to have been present in South America south of 15° S, in Africa south of 10° S, in India between 15° and 30° N and in Australia. In the Andean region Alpine glaciers or mountain ice caps may have developed; in eastern Brazil near Buenos Aires, a mountain ice cap or a continental ice sheet, possibly the former, may have been present. In Africa north of about 30° S to about 5° N, alpine glaciers or mountain ice caps may have developed, and in the Karroo to the south there may have been a continental ice sheet. In India a mountain ice cap possibly existed about and to the north of 20° N. In Australia alpine glaciers or mountain ice caps seem to have been present, but to my mind the presence of a continental ice sheet is extremely doubtful.

Belts of loess have not been distinguished associated with any of these ice masses.

Our knowledge of Antarctica and the Arctic regions is very deficient. Our inability to say what conditions were in these areas during Sakmarian times makes our speculations on the positions of climatic belts and consequently on the positions of the poles, equator and continents unrewarding. It is to be hoped that the great scientific activity in Antarctica this year will throw light on the occurrence of *Glossopteris*-bearing sediments

FIG. 8 MAXIMUM EXTENT OF SAKMARIAN GLACIATION & MARINE TRANSGRESSIONS

there, and show whether, as in South America, such are interbedded with glacials as yet unrecognised.

Climatic belts. If we accept the assumption of Sakmarian age for these glacial deposits, sufficient precipitation, low enough temperatures and sufficient relief for mountain ice caps or small continental ice sheets to form must have occurred between 20° and 40° S.

Asia was humid enough for coals to form between 40° and 60° N, and in W. Europe coal formed mainly in intramontane basins; the eastern part of the U.S.A. (about 40° N) was humid enough for coal formation, while western U.S.A. between 20° and 50° N was probably a rather arid temperate region of seasonal rainfall. At present we know of no Sakmarian glacials in either Antarctica or the Arctic Regions. Beyond these generalisations we cannot go as yet.

Conclusions

1. A reasonable northern hemisphere map of Sakmarian land and sea surfaces can be constructed from the known palaeontological and stratigraphical data. Sea surfaces were very much enlarged and land surfaces very much reduced. This could have had considerable influence on circulation and on climate.

2. A similar map for the southern hemisphere depends on somewhat risky assumptions being made in the correlation of faunas and strata. Land surfaces are but slightly reduced.

3. If these assumptions in correlation are made, glacial deposits were developed mainly in a belt between 40° S and 20° S; but no undoubted glacials are known in the northern hemisphere, except in India.

4. The glacials appear to be mainly from mountain ice caps and valley glaciers, though small continental ice caps may have been present in the Karroo and Parana Basins.

5. The roughly concentric development of the glacials about the present South Pole suggests that they form a climatic zone about a Sakmarian Pole approximately in todays position, but the present evidence gives no clear-cut support for either fixity or mobility of poles or continents.

6. Two problems need solution before a really reliable map of Sakmarian climatic belts can be drawn and hypotheses of polar wandering and continental drift tested. These are the Sakmarian history of Antarctica and the Arctic Regions, and the correlation of the "Gondwana" faunas and floras with those of the northern hemisphere.

References

Europe

Backlund, H. G., 1930. On a probable tillite of late Palaeozoic age from the Kara-River, northern-most Ural. C. R. 15th Int. geol. Congr., Vol. 2, pp. 77—82. — Bankovitch, V. A., and Redisykin, N. A., 1955. [*Schwagerina* horizon in the North East of the Donetz Basin.] C. R. Acad. Sci. U.R.S.S. 1955, **104**, pp. 456—458. — Dunbar, C. O., 1940. The type Permian: Its classification and correlation. Bull. Amer. Assoc. Petrol. Geol., **24**, pp. 237—281. – 1942.

Artinskian Series (Discussion). Bull. Amer. Assoc. Petrol. Geol., **26,** pp. 402—409. — Fomichev, V. D., 1953. [Rugose corals and stratigraphy of the Middle and Upper Carboniferous and Permian deposits of the Donetz Basin.] Trudy vsesoyuz. nauch.-issled. geol. Inst., pp. 1—622, pls. 1—44. — Francis, W., 1954. Coal; its formation and composition. E. Arnold, London. — Heritsch, F., 1939. Karbon und Perm in den Südalpen und in Südosteuropa. Geol. Rdsch., **30,** pp. 529—588. — Ignatiev, V. I., 1952. Das Relief der permischen Zeit im Einzugsgebiet der unteren Oka. C. R. Acad. Sci. U.R.S.S. (2) **84,** pp. 1037—1040, 1/9. — Jongmans, W. J., 1952 a. Some problems on Carboniferous stratigraphy. C. R. 3ième Congr. Stratig. Géol. Carb. I, pp. 295—306. – 1952 b. Discussion on paper by G. Mathieu. C. R. 3ème Congr. Stratig. Géol. Carb. II, pp. 449—451. — Kopeliovitch, A. B., and Eventov, Y. S., 1956. Permian deposits of Astrakhan. C. R. Acad. Sci. U.R.S.S., **106,** No. 2, pp. 320—323. — Likharev, B. K., 1937. Permian System of the U.R.S.S., certain problems of its stratigraphy and correlations with other countries. Abstr. Pap. 17th Int. geol. Congr., p. 81. — Maximova, S. W., 1952. [On the palaeofaunistic character of the Sakmarian Stage.] Bull. Acad. Sci. U.R.S.S. (Geol.), **3,** pp. 118—127, 1 pl. — Miller, A. K., 1938. Comparison of Permian ammonoid zones of Soviet Russia with those of North America. Bull. Amer. Assoc. Petrol. Geol., **22,** pp. 1014—1019. — Nalivkin, D. V., 1937. The Sim Works. 17th Int. geol. Congr. Perm Excursion (S. Part). p. 123. – 1938. Scientific results of the Permian conference. Bull. Amer. Assoc. Petrol. Geol., **22,** pp. 771—776. — Rozovskaya, S. E., 1949. [Stratigraphic distribution of fusulinids in Upper Carboniferous and Lower Permian localities of the Southern Ural.] C. R. Acad. Sci. U.R.S.S., **69,** pp. 249—252. — Rakusz, G., 1932. Die oberkarbonischen Fossilien von Dobsina und Nagyvisnyo. Geol. hung. (b), **8,** pp. 1—224, pls. 1—9. — Ruzhentsev, V. E., 1951. Lower Permian Ammonoids of the Southern Urals. I. Ammonites of the Sakmarian stage. Trav. Paleont. Inst. Acad. Sci. U.R.S.S., **33,** pp. 1—188, pls. 1—15. – 1954. [Asselian stage of the Permian System.] C. R. Acad. Sci. U.R.S.S., **99,** pp. 1079—1082. – 1956. Lower Permian Ammonites of the Southern Urals, II. Ammonites of the Artinskian Stage. Trav. Paleont. Inst. Acad. Sci. U.R.S.S., **60,** pp. 1—275, pls. 1—39. — Ruzhentsev, V. E., and Shimansky, V. N., 1954. [Lower Permian coiled and curved nautiloids of the Southern Urals.] Trav. Paleont. Inst. Acad. Sci. U.R.S.S., **50,** pp. 1—152, pls. 1—15. — Shimansky, V. N., 1954. [Straight nautiloids and bactritids of the Sakmarian and Artinskian stages of the southern Urals.] Trav. Paleont. Inst. Acad. Sci. U.R.S.S., **44,** pp. 1—156, pls. 1—12. — Sujkowski, Z., 1946. The geological structure of East Poland and West Russia: a summary of recent discoveries. Quart. J. geol. Soc., **102,** pp. 189—201. — Sultanaev, A. A., 1954. Stratigraphic scheme for the upper Palaeozoic of the Kolvo-Vishersk region. C. R. Acad. Sci. U.R.S.S., **98,** pp. 257—258. — Tolstikhina, M. M., 1937. Upper Paleozoic reefs on the western slope of the Urals. Abstr. Pap. 17th Int. geol. Congr., p. 97. — Toumansky, O. G., 1937. Les depôts permiens de la Crimée. Abstr. Pap. 17th Int. geol. Congr., p. 108. — Wilser, J. L., 1927. Die Steinkohlen in der Schwarzmeer-Umrandung, insbesondere bei Heraklea-Zonguldag (Nordanatolien). Geol. Rdsch., **18,** pp. 1—37.

Asia

Bemmelen, R. W. van, 1949. The Geology of Indonesia. 2 vols. The Hague. — Chibber, H. L., 1934. The Geology of Burma. Macmillan & Co., London. — Douglas, J., 1950. The Carboniferous and Permian faunas of South Iran and Iranian Baluchistan. Palaeont. Indica, **22,** No. 7, pp. 1—57, pls. i—v. — Dunbar,

C. O., 1933. Stratigraphic significance of the fusulinids of the Lower Productus Limestone of the Salt Range. Rec. geol. Surv. India, **66**, pp. 405—413, pl. 22. — DUNBAR, C. O., and MISCH, P., 1947. Fusuline-bearing Permian rocks of northwestern Yunnan. Bull. geol. Soc. China, **27**, pp. 101—110. — DUTKIEWICZ, G. A., 1937. Le paléozoique supérieur du Pamir et du Darvaz. Abs. Pap. 17th Int. geol. Congr., p. 105. — ENDO, R., 1953. A summary of the columnar section in Manchuria. Proc. 7th Pan-Pacif. Sci. Congr., Vol. 2, pp. 316—326. — FOX, C. S., 1937. The climates of Gondwanaland during the Gondwana era in the Indian region. Abs. Pap. 17th Int. geol. Congr., p. 216. — FROMAGET, J., 1952. Aperçu de nos connaissances sur la géologie de l'Indochine. Rept. 18th Int. geol. Congr., XIII, pp. 63—77. — GERTH, H., 1950. Die Ammonoideen des Perms von Timor und ihre Bedeutung für die stratigraphische Gliederung der Permformation. Abh. N. Jb. Min., Geol., Paläont. (B), **91**, pp. 233—320. — 1952. Das Klima des Permzeitalters. Geol. Rdsch., **40**, pp. 84—89. — GRABAU, A. W., 1931. The Permian of Mongolia. Amer. Mus. nat. Hist. New York. — HAYASAKA, I., 1954. Younger Palaeozoic cephalopods from the Kitakami Mountains. J. Fac. Sci. Hokkaido Univ. Ser. IV, **8**, pp. 361—374. — JACOB, K., 1952. A brief summary of the stratigraphy and palaeontology of the Gondwana system. Symposium sur les Series de Gondwana. 19th Int. geol. Congr., pp. 153—174. — JONGMANS, W. J., 1939. Die Kohlenbecken des Karbons und Perms in U.S.S.R. und Ostasien. Geol. Sticht., Jaarsverslag 1934—37, pp. 15—192. — KAHLER, F. and G., 1940. Fusuliniden aus dem Tienschan. N. Jb. Min. Geol. Paläont. Abh. (B), **83**, pp. 348—362, pls. 8—10. — KOBAYASHI, T., 1942. The Akiyoshi orogenic cycle in the Mongolian geosyncline. Proc. imp. Acad. Tokyo, **18**, pp. 306—319. – 1952. On the southwestern wing of the Akiyoshi orogenic zone in Indochina and South China and its tectonic relationship with the other wing in Japan. Jap. J. Geol. Geogr., **22**, pp. 27—37. — LEE, J. S., 1939. The Geology of China. Murby & Co., London. — LEUCHS, K., 1935. Geologie von Asien. Vol. 1, parts 1 and 2, Borntraeger, Berlin. — LICHAREV, B. K., 1937. Permian brachiopods of the U.R.S.S. Abs. Pap. 17th Int. geol. Congr., p. 97. — MA, T. Y. H., 1955. Climate and the relative positions of the continents during the Lower Carboniferous. Res. past Climate continental Drift, **7**, pp. 1—99, pls. 1—50. — MINATO, M., 1953. Palaeogeographie des Karbons in Ostasien. Proc. Jap. Acad., **29**, pp. 246—253. – 1955. Japanese Carboniferous and Permian corals. J. Fac. Sci. Hokkaido Univ., Ser. IV, **9**, No. 2, pp. 1—202, pls. 1—43. – 1956. Paleogeography of the Japánese Islands and their adjacent lands in the Upper Palaeozoic era. Reprint in Japanese, pp. 1—13. — NORIN, E., 1930. An occurrence of late Palaeozoic tillite in Kurak-tagh Mts., Central Asia. C. R. 15th Int. geol. Congr., Vol. 2, pp. 74—76. — OBRUTSCHEW, W. A., 1926. Geologie von Sibirien. Fortschr. Geol., Heft 15, 572 pp., 1 map, 10 pls., 60 text figs. — STOYANOW, A., 1942. Revision of the Permo-Triassic sequence at Djulfa, Armenia. Bull. geol. Soc. Amer., **53**, p. 1823. — TCHIRKOVA, H. T., and ZALESSKY, M. D., 1939. Carte de l'extension du continent de l'Angaride d'après les découvertes de la flore Permienne. Probl. Sov. Palaeont., **5**, pp. 311—322. — THOMPSON, M. L., 1936. Lower Permian fusulinids from Sumatra. J. Paleont., **10**, pp. 587—592, figs. 1—13. – 1946. Permian fusulinids from Afghanistan. J. Paleont., **20**, pp. 140—157, pls. 23—26, text fig. 1. – 1949. The Permian fusulinids of Timor. J. Paleont., **23**, pp. 182—192, pls. 34—36. — THOMPSON, M. L., and MILLER, A. K., 1935. *Schwagerina* from the western edge of the Red Basin, China. J. Paleont., **9**, pp. 647—652. — USTRISHKY, V. I., 1955. Brachiopod complex of the Permian deposits of East Taimyr. C. R. Acad. Sci. U.R.S.S., **105**, pp. 805—807. — WADIA, D. N., 1937. Note on the Palaegeography and climate

of Kashmir during the Permo-Carboniferous. Abs. Pap. 17th Int. geol. Congr., pp. 218—219. – 1953. The Geology of India. 3rd Edit. Macmillan & Co., London. — Weir, J., 1945. A review of recent work on the Permian non-marine lamellibranchs and its bearing on the affinities of certain non-marine genera of the Upper Palaeozoic. Trans. geol. Soc. Glasg., **20**, pp. 291—340.

North America

Agatson, R. S., 1954. Pennsylvanian and Lower Permian of northern and eastern Wyoming. Bull. Amer. Assoc. Petrol. Geol., **38**, pp. 508—583. — Baker, A. A., Huddle, J. W., and Kinney, D. M., 1949. Paleozoic geology of north and west sides of Uinta Basin, Utah. Bull. Amer. Assoc. Petrol. Geol., **33**, pp. 1161—1197. — Baker, A. A., and Williams, J. S., 1940. Permian in parts of Rocky Mountain and Colorado Plateau regions. Bull. Amer. Assoc. Petrol. Geol., **24**, pp. 617—635. — Blackstone, D. L., 1954. Permian rocks in Lemhi Range, Idaho. Bull. Amer. Assoc. Petrol. Geol., **38**, pp. 923—925. — Brill, K. G., 1952. Stratigraphy in the Permo-Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico. Bull. geol. Soc. Amer., **63**, pp. 809—880, 3 pls. — Cressman, E. R., 1955. Physical stratigraphy of the Phosphoria Formation in part of southwestern Montana. Bull. U.S. geol. Surv., 1027-A, pp. 1—31, pls. 1—5. — Cross, A. T., and Arkle, T., 1952. The stratigraphy, sedimentation and nomenclature of the Upper Pennsylvanian-Lower Permian (Dunkard) strata of the Appalachian area. C. R. 3ième Congr. Stratig. Carbon., I, pp. 101—111. — Dott, R. H., 1955. Pennsylvanian stratigraphy of Elko and northern Diamond Ranges, N.E. Nevada. Bull. Amer. Assoc. Petrol. Geol., **39**, pp. 2211—2305. — Dunbar, C. O., 1924. Was there Pennsylvanian-Permian glaciation in the Arbuckle and Wichita Mountains of Oklahoma? Amer. J. Sci., **8**, pp. 241—248. – 1939. Permian fusulines from Sonora. Bull. geol. Soc. Amer., **50**, pp. 1745—1760, 4 pls. – 1955. Permian brachiopod faunas of central east Greenland. Medd. Grønland, **110**, No. 3, pp. 1—170, pls. 1—32. — Eardley, A. J., 1951. Structural geology of North America. 624 pp. Harper, New York. — Fortier, Y. O., Mcnair, A. H., and Thorsteinsson, R., 1954. Geology and Petroleum Possibilities in Canadian Arctic Islands. Bull. Amer. Assoc. Petrol. Geol., **38**, pp. 2075—2109. — Frebold, H., 1950. Stratigraphie und Brachiopodenfauna des marinen Jungpaläozoikums von Holms- und Amdrups-Land (Nordostgrönland). Medd. Grønland, **126**, No. 3, pp. 1—97, pls. 1—6. — Hills, J. M., 1942. Rhythm of Permian seas — a paleogeographic study. Bull. Amer. Assoc. Petrol. Geol., **26**, pp. 217—255. — Imlay, R. W., 1939. Paleogeographic studies in northeastern Sonora. Bull. geol. Soc. Amer., **50**, pp. 1723—2744, 4 pls. — Kay, M., 1951. North American geosynclines. Mem. geol. Soc. Amer., **48**, pp. 1—143, pls. 1—16. — King, P. B., 1948. Geology of the southern Guadalupe Mountain Texas. Prof. Pap. U.S. Geol. Surv., **215**, pp. 1—183, pls. 1—23. – 1951. The tectonics of middle North America. 203 pp. Princeton. — King, R. E., 1939. Geological reconnaissance in northern Sierra Madre Occidental of Mexico. Bull. geol. Soc. Amer., **50**, pp. 1625—1722, 9 pls. — King, R. E., Dunbar, C. O., Cloud, P. E., and Miller, A. K., 1944. Geology and Paleontology of the Permian area Northwest of Las Delicias, Southwestern Coahuila, Mexico. Sp. Pap. geol. Soc. Amer., **52**, pp. 1—172, pls. 1—45. — Lloyd, E. R., 1949. Pre-San Andres stratigraphy and oilproducing zones in Southeastern New Mexico. Bull. N. Mex. Bur. Min., **29**, pp. 1—87, pls. 1—10. — Lord, C. S., Hage, C. O., and Stewart, J. S., 1947. The Cordilleran region in Geology and economic minerals of Canada. 3rd Edit. Geol. Surv. Can., Econ. Geol., pp. 220—310. — Lovering, T. S., and Goddard, E. N., 1950. Geology and Ore

deposits of the Front Range, Colorado. Prof. Pap. U.S. geol. Surv., **223**, pp. 1—319, pls. 1—30. — McCabe, W. S., 1954. Williston Basin Paleozoic unconformities. Bull. Amer. Ass. Petrol. Geol., **38**, pp. 1997—2010. — McKee, E. D., 1951. Sedimentary basins of Arizona and adjoining areas. Bull. geol. Soc. Amer., **62**, pp. 481—506, 3 pls. — McKelvey, V. E., Swanson, R. W., and Sheldon, R. P., 1953. The Permian phosphorite deposits of western United States. C. R. 19th Int. geol. Congr. Sec. XI, pp. 45—64. — McLearn, F. H., and Kindle, E. D., 1950. Geology of Northeastern British Columbia. Mem. geol. Surv. Can., **259**, pp. 1—236, pls. 1—8, map. — McNair, A. H., 1951. Paleozoic stratigraphy of part of north western Arizonia. Bull. Amer. Assoc. Petrol. Geol., **35**, pp. 503—541. — Maher, J. C., 1954. Lithofacies and suggested depositional environment of Lyons Sandstone and Lykins Formation in Southeastern Colorado. Bull. Amer. Assoc. Petrol. Geol., **38**, pp. 2233—2239. — Miller, A. K., and Youngquist, W., 1949. American Permian nautiloids. Mem. geol. Soc. Amer., **41**, pp. 1—218, pls. 1—59. — Moffit, F. H., 1954. Geology of the eastern part of the Alaska Range and adjacent areas. Bull. U.S. geol. Surv., 989-D, pp. 60—218, pls. 6, 7. — Moore, R. C., Frye, J. C., Jewett, J. M., Lee, W., and O'Connor, H. G., 1951. The Kansas rock Column. Bull. geol. Surv. Kansas, **89**, pp. 1—132. — Mullerried, F. K. G., Miller, A. K., and Furnish, W. M., 1941. The Middle Permian of Chiapas, southernmost Mexico, and its fauna. Amer. J. Sci., **239**, pp. 397—406, 1 pl. — Newell, N. D., 1948. Key Permian section, Confusion Range, western Utah. Bull. geol. Soc. Amer., **59**, pp. 1053—1058. — Nolan, T. B., 1943. The Basin and Range Province in Utah, Nevada and California. Prof. Pap. U.S. geol. Surv., 197-D, pp. 141—196, pl. 40, 41. — Roots, E. F., 1954. Geology and mineral deposits of Aiken Lake Map-Area, British Columbia. Mem. geol. Surv. Can., **274**, pp. 1—246, pl. i—x, maps. — Sapper, K., 1937. Mittelamerika. Handb., reg. Geol. VIII, 4 a, pp. 1—160, pls. I—X. — Schuchert, C., 1935. Historical Geology of the Antillean Caribbean Region. 811 pp. New York and London. — Smith, P. S., 1939. Areal geology of Alaska. Prof. Pap. U.S. Geol. Surv., **192**, pp. 1—100, pls. 1—18, 1 chart. — Thompson, M. L., 1954. American Wolfcampian fusulinids. Univ. Kansas, Paleont. Contrib., Protozoa. Art., **5**, pp. 1—226, pls. 1—52. — Thompson, M. L., and Miller, A. K., 1944. The Permian of southernmost Mexico and its fusulinid faunas. J. Palaeont., **18**, pp. 481—504, pls. 79—84. — Thompson, M. L., Wheeler, H. E., and Hazzard, J. C., 1946. Permian fusulinids of California. Mem. geol. Soc. Amer., **17**, pp. 1—77, pls. 1—18. — Troelsen, J. C., 1950. Contributions to the geology of Northwest Greenland, Ellesmere Island and Axel Heiberg Island. Medd. Grønland., **149**, No. 7, pp. 1—86, 1 map. — Wanless, H. R., et al., 1955. Paleozoic and Mesozoic rocks of Grosventre, Teton, Hoback, and Snake River Ranges, Wyoming. Mem. geol. Soc. Amer., **63**, pp. 1—90, pls. 1—13. — Wengerd, S. A., and Strickland, J. W., 1954. Pennsylvanian stratigraphy of Paradox Salt Basin, Four Corners Region, Colorado and Utah. Bull. Amer. Ass. Petrol. Geol., **38**, pp. 2157—2199. — Wheeler, H. E., 1940. Permian volcanism in western North America. Proc. 6th Pan. Pacif. Sci. Congr., I, pp. 369—376.

South America

Adie, R. J., 1952. Representatives of the Gondwana System in the Falkland Islands. Symposium sur les Séries de Gondwana. 19th Int. geol. Congr., pp. 385—392. — Ahlfeld, F., 1946. Geologia de Bolivia. Rev. Mus. La Plata (NS), **3**, Sec. Geol., pp. 11—370, 115 figs., map. — Almeida, F. F. M. de, 1952. État actuel des connaissances sur la formation de Gondwana, au Bresil. Symposium sur les Séries de Gondwana. 19th Int. geol. Congr., pp. 258—272. — Barbosa,

O., 1952. Comparison between the Gondwana of Brazil, Bolivia, and Argentina. Symposium sur les Séries de Gondwana. 19th Int. geol. Congr., pp. 313—324. — BEURLEN, K., 1957. Das Gondwana-Inlandeis in Südbrasilien. Geol. Rdsch., 45, pp. 595—599. — CASTER, K. E., 1952. Stratigraphic and paleontologic data relevant to the problem of Afro-American ligation during the Paleozoic and Mesozoic. Bull. Amer. Mus. nat. Hist., **99**, pp. 105—158, pls. 17—18, text figs. 1—17. — CASTER, K. E., and DRESSER, H., 1954. Contributions to knowledge of the Brazilian Paleozoic: No. 1. Bull. Amer. Pal., **35**, No. 149, pp. 1—84, 8 pls. — DOLIANTE, E., 1952. La flore fossile du Gondwana au Brésil d'après sa position stratigraphique. Symposium sur les Séries de Gondwana. 19th Int. geol. Congr., pp. 285—301. — FOSSA-MANCINI, E., 1944. Las transgresiones marinas del Antracolitico en la America del Sur. Rev. Mus. La Plata (NS) **2**, Sec. Geol., pp. 49—183. — FRENGUELLI, J., 1944. Apuntes acerca del Paleozoico Superior del Noroeste Argentino. Rev. Mus. La Plata (NS) **2**, Sec. Geol., pp. 213—265. – 1946. Consideraciones acerca de la "Serie de Paganzo" en las provinces de San Juan y La Rioja. Rev. Mus. La Plata (NS) **2**, Sec. Geol., pp. 313—376. — GERTH, H., and KRÄUSEL, R., 1931. Beiträge zur Kenntnis des Carbons in Südamerika, I. Neue Vorkommen von marinem Obercarbon in den nördlichen Anden. N. J. Min. Geol. Paläont. (B) Bd., **65**, Abt. pp. 521—529, pl. 22. — HARRINGTON, H. J., 1950. Geologia del Paraguay oriental. Contr. Sci. Univ. Buenos Aires, Ser. E (Geol.), Vol. 1, pp. 1—82, pls. 1—3, 2 maps. – 1955. The Permian *Eurydesma* fauna of eastern Argentina. J. Paleont., **29**, pp. 112—128, pls. 23—26. — HEIM, A., 1945. Observaciones tectonicas en Barreal. Precordillera de San Juan. Rev. Mus. La Plata (NS) **2**, Sec. geol., pp. 267—286. — KEGEL, W., 1953. Das Paläozoikum des Parnaiba-Beckens (Piaui und Maranhao, Brasilien). 19th Int. geol. Congr. Sec. II, Fasc. II, pp. 165—169. — KOZLOWSKI, R., 1914. Les brachiopodes du Carbonifère supérieur de Bolivie. Ann. Paleont., **9**, 102 pp., 11 pls. — MAACK, R., 1957. Über Vereisungsperioden und Vereisungsspuren in Brasilien. Geol. Rdsch., **45**, pp. 547—595. — MENDES, J. C., 1952. Invertébrés du Système de Gondwana au Brésil. Symp. Séries de Gondwana, 19th Int. geol. Congr., pp. 302—307. – 1957. Das Karbon des Amazonas-Beckens. Geol. Rdsch., **45**, pp. 540—546. — MILLER, A. K., and WILLIAMS, J. S., 1945. Permian cephalopods from northern Colombia. J. Paleont., **19**, pp. 347—349, pl. 51. — MILLER, A. K., and GARNER, M. F., 1953. Upper Carboniferous goniatites from Argentina. J. Paleont., **27**, pp. 821—823. — NEWELL, N. D., CHRONIC, J., and ROBERTS, T. G., 1953. Upper Paleozoic of Peru. Mem. geol. Soc. Amer., **58**, pp. 1—276, pls. 1—44. — OLIVEIRA, A. I. DE, and LEONARDOS, O. H., 1943. Geologia do Brasil. 2nd Edit. Sér. didát. Serv. Inf. agric. Rio de J., No. 2, 813 pp., 37 pls. of fossils; map. — PUTZER, H., 1957. Beziehungen zwischen Inland-Vereisung und Kohlebildung in Oberkarbon von Südbrasilien. Geol. Rdsch., **45**, pp. 599—608. — REED, F. R. C., 1927. Upper Carboniferous fossils from Argentina in Du Toit, A. L., A geological comparison of South America with South Africa. Publ. Carnegie Inst., **381**, pp. 129—150, pls. 13—16. — SUERO, T., 1952. Las sucesiones sedimentarias suprapaleozoicas de la zona extraandina del Chubut (Patagonia Austral — Republica Argentina). Symposium sur les Séries de Gondwana. 19th Int. geol. Congr., pp. 373—384. — SUERO, T., and ROQUE, P. C., 1955. Descubrimiento de Paleozoico superior al oeste de Bahia Laura (Terr. Nac. de Santa Cruz) y su importancia paleogeográfica. Not. Mus. Univ. Nac. Eva Peron, XVIII, Geol. No. 68, pp. 157—168. — THOMPSON, M. L., and MILLER, A. K., 1949. Permian fusulinids and cephalopods from the vicinity of the Maracaibo basin in northern South America. J. Paleont., **23**, pp. 1—24, pls. 1—8.

Africa

Astre, G., 1934. La Faune permienne des grès à *Productus* d'Ankitokazo dans le Nord de Madagascar. Ann. geol. Serv. Min. Madagascar, fasc. 4, 4 pls. — Besairie, H., 1952. Les formations du Karroo à Madagascar. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana, pp. 181—186. — Bond, G., 1952. The Karroo System in Southern Rhodesia. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana, pp. 209—223. — Borges, A., 1952. Le Systeme du Karroo au Moçambique. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana, pp. 232—250. — Borges, A., Nunes, A., and Freitas, F., 1954. Contribution to the data on the Karroo of Portuguese Lake Nyasa. C. R. 19th Int. geol. Congr. Fasc. 21, pp. 83—92. — Brandt, R. T., 1954. Notes on the Karroo System in Northern Rhodesia. C. R. 19th Int. geol. Congr. Fasc. 21, pp. 63—70. — Cahen, L., 1954. Géologie du Congo belge, pp. 1—577, Liege. — Cox, L. R., 1936. Karroo Lamellibranchia from Tanganyika Territory and Madagascar. Quart. J. geol. Soc., **92,** pp. 32—57, pls. 4, 5. — Davies, K. A., 1952. Karroo System in Uganda. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana, pp. 191—194. — Dixey, F., and Willbourn, E. S., 1951. The geology of the British African colonies. C. R. 18th Int. geol. Congr. Fasc. XIV, pp. 87—109. — Efremov, I. A., and Vjuschkov, B. I., 1955. [Catalogue of localities for Permian Triassic Reptiles in the Territories of the U.S.S.R.] Trav. Palaeont. Inst. Acad. Sci. U.R.S.S., **46,** pp. 1—185. — Green, D., and Poldervaart, A., 1954. Coal in the Bechuanaland Protectorate. C. R. 19th Int. geol. Congr. Fasc., **21,** pp. 71—82. — Gürich, G., 1923. *Acrolepis Lotzi* und andere Ganoiden aus den Dwyka-Schichten von Ganikobis, Südwestafrika. Beitr. geol. Erforsch. dtsch. Schbeb. Heft **19,** Part II, pp. 26—74, pls. 1—3. — Harkin, D. A., McKinlay, A. C. M., and Spence, J., 1954. The Karroo System of Tanganyika. C. R. 19th Int. Geol. Congr. Fasc., **21,** pp. 93—102. — Haughton, S. H., 1952. The Karroo System in the Union of South Africa. 19th Int. geol. Congr. Symposium sur les Series de Gondwana, pp. 254—255. – 1953. Gondwanaland and the distribution of early reptiles. Annex. to Vol. 56, Trans. geol. Soc. S. Afr., pp. 1—30. — Haughton, S. H., Blignaut, J. J. G., Rossouw, P. J., Spies, J. J., and Zagt, S., 1953. Results of an investigation into the possible presence of oil in Karroo rocks in parts of the Union of South Africa. Mem. geol. Surv. S. Afr., **45,** 130 pp. — Huene, F. von, 1940. Die Saurier der Karroo-, Gondwana- und verwandten Ablagerungen in faunistischer, biologischer und phylogenetischer Hinsicht. N. Jb. Min. Geol. Palaont. Abh. Abt. B, **83,** pp. 246—347. — Jongmans, W. J., 1952. Some problems on Carboniferous stratigraphy. C. R. 3ième Congr. Strat. Geol. Carb. I, pp. 295—306. — MacGregor, A. M., 1947. An outline of the geological history of Southern Rhodesia. Bull. geol. Surv. S. Rhodesia, **38,** 73 pp. — Martin, H., 1950. Südwestafrika. Geol. Rdsch., **38,** pp. 6—14. – 1954. Notes on the Dwyka succession and on some pre-Dwyka valleys in S. W. Africa. Trans. geol. Soc. S. Afr., **56,** pp. 37—43, pl. 5. — Mouta, F., and Cahen, L., 1951. Le Karroo du Congo Belge et de l'Angola. C. R. 18th Int. geol. Congr. Fasc. XIV, pp. 270—281. — Rilett, M. H. P., 1955. Plant microfossils from the coal seams near Dannhauser, Natal. Trans. geol. Soc. S. Afr., **57,** pp. 27—38, pl. v. — Rock, E., 1950. Histoire stratigraphique du Maroc. Notes Mem. Serv. geol. Maroc., **80,** pp. 1—435, pls. 1—22. — Teixeira, C., 1951. Present state of our knowledge concerning the palaeontology of the Karroo of Portuguese Africa. C. R. 18th Int. geol. Congr. Fasc. XIV, pp. 214—217. — Temperley, B. N., 1952. A review of the Gondwana rocks of Kenya Colony. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana,

pp. 195—208. — Wagner, P. A., 1916. The Geology and Mineral Industry of South-West Africa. Mem. geol. Surv. S. Afr., **7**, pp. 1—119, pls. 1—41, map. — Wayland, W. J., 1952. Karroo System of Bechuanaland Protectorate. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana, pp. 251—253.

Antarctica

Adie, R. J., 1952. Representatives of the Gondwana System in Antarctica. 19th Int. geol. Congr. Symposium sur les Séries de Gondwana. pp. 393—399. — Seward, A. C., 1914. Antarctic fossil plants. British Antarctic ("Terra Nova") Expedition, 1910. Geology Vol. 5, pp. 1—49, pls. 1—8, 3 maps.

Australia, New Guinea and New Zealand

Campana, B., and Wilson, R. B., 1955. Tillites and related glacial topography of South Australia. Ecl. geol. Helv., **48**, pp. 1—30, pls. 1—4. — Glaessner, M. F., Llewellyn, K. M., and Stanley, G. A. V., 1950. Fossiliferous rocks of Permian age from the Territory of New Guinea. Aust. J. Sci., **13**, pp. 24—25. — Hill, D., 1950. The Productinae of the Artinskian Cracow fauna of Queensland. Pap. Dept. Geol. Univ. Qd., **3**, (11), pp. 1—27, pls. 1—9. – (reviewer) 1955. Contributions to the correlation and fauna of the Permian in Australia and New Zealand. J. geol. Soc. Aust., **2**, pp. 83—107. — Ludbrook, N. H., 1957. Permian Foraminifera in South Australia. Aust. J. Sci., **19**, pp. 161—162. — Maxwell, W. G. H., 1954. *Strophalosia* in the Permian of Queensland. J. Paleont., **28**, pp. 533—559, pls. 54—57. — Rickwood, F. K., 1955. The geology of the Western Highlands of New Guinea. J. geol. Soc. Aust., **2**, pp. 63—82, pls. 1—4. — Thomas, G. A., 1954. Correlation and faunal affinities of the marine Permian of Western Australia. Proc. Pan-Ind. Ocean Sci. Congr. (C), pp. 5—6.

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STRATIGRAPHY AND MICROPALAEONTOLOGY OF THE UPPER CRETACEOUS OF WESTERN AUSTRALIA

by D. J. Belford *)

with 9 Figures

Abstract

The distribution, relationships, and stratigraphical significance of the microfaunas (mainly foraminifera) in the Upper Cretaceous deposits of Western Australia are discussed, and palaeogeography and palaeoecology considered.

Formations deposited during the Cenomanian—Turonian are the Gearle Siltstone and Alinga Greensand and perhaps the Molecap Greensand. Among the foraminifera recorded are the stratigraphically restricted planktonic forms *Globotruncana (Praeglobotruncana) stephani* subspp. and *G. helvetica*.

The Gingin Chalk and the lower part of the Toolonga Calcilutite were deposited during the Santonian. These formations contain the crinoid genera

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Marsupites and *Uintacrinus*, several species of *Globotruncana* and *Neoflabellina*, and *Bolivinoides strigillata*. Santonian beds are known in sub-surface sections as far north as the area of the Warroora Anticline.

The Toolonga Calcilutite extends up into the lower Campanian, and *Globotruncana arca* appears in the fauna. The occurrence of Campanian beds in the Perth Basin cannot be proved; most of the Poison Hill Greensand may be of this age. On foraminiferal evidence, deposition of the Korojon Calcarenite began during the Campanian. Important species identified are *Globotruncana arca*, *Cibicides voltziana* and *Bolivina incrassata*.

The upper beds of the Korojon Calcarenite and the Miria Marl are of Maestrichtian age. The Miria Marl contains the species *Globotruncana stuarti*, *G. citae* and *G. contusa*. The upper beds of the Poison Hill Greensand may range into the Maestrichtian.

Introduction

This paper reviews the present knowledge of the distribution and relationships of the Upper Cretaceous foraminifera of Western Australia; their stratigraphical and palaeogeographical significance is also considered. Much of the information presented here has been obtained from samples forwarded by West Australian Petroleum Pty. Ltd., and permission from the Company to use this information is gratefully acknowledged.

Upper Cretaceous microfaunas were first recorded from Western Australia almost 50 years ago, but knowledge of their distribution and relationships was very incomplete until detailed field work was begun in the Carnarvon Basin by geologists of the Bureau of Mineral Resources in 1948. Surface samples collected in the Carnarvon Basin by geologists of the Bureau since that time have been examined for microfossils; examination of surface and sub-surface samples collected by West Australian Petroleum Pty. Ltd. during the search for oil in Western Australia has also greatly increased knowledge of the microfaunas. Investigations have up to the present been carried out mainly in the area of the Carnarvon Basin, and the foraminifera have enabled correlations to be made with areas outside Australia.

Outline of Geology

In Western Australia, Upper Cretaceous marine sediments are known only in the Carnarvon Basin, which extends from Onslow in the north to the Murchison River in the south, and in the Perth Basin, near Gingin and Dandaragan. The most northerly outcrop in the Carnarvon Basin is on the Giralia Anticline; the geology of this area is described by Condon, Johnstone, Prichard and Johnstone (1956). The Upper Cretaceous sequence includes siltstone, calcarenite, and marl, with unconformities in the section. The same sequence was penetrated in bores drilled by West Australian Petroleum Pty. Ltd. on the Cape Range and Rough Range structures, where Upper Cretaceous beds are covered by Tertiary and younger deposits. Upper Cretaceous deposits are also recorded from water bores near Carnarvon, notably the Brickhouse Station Water Bores Nos. 1 and 4 and the Pelican Hill Bore.

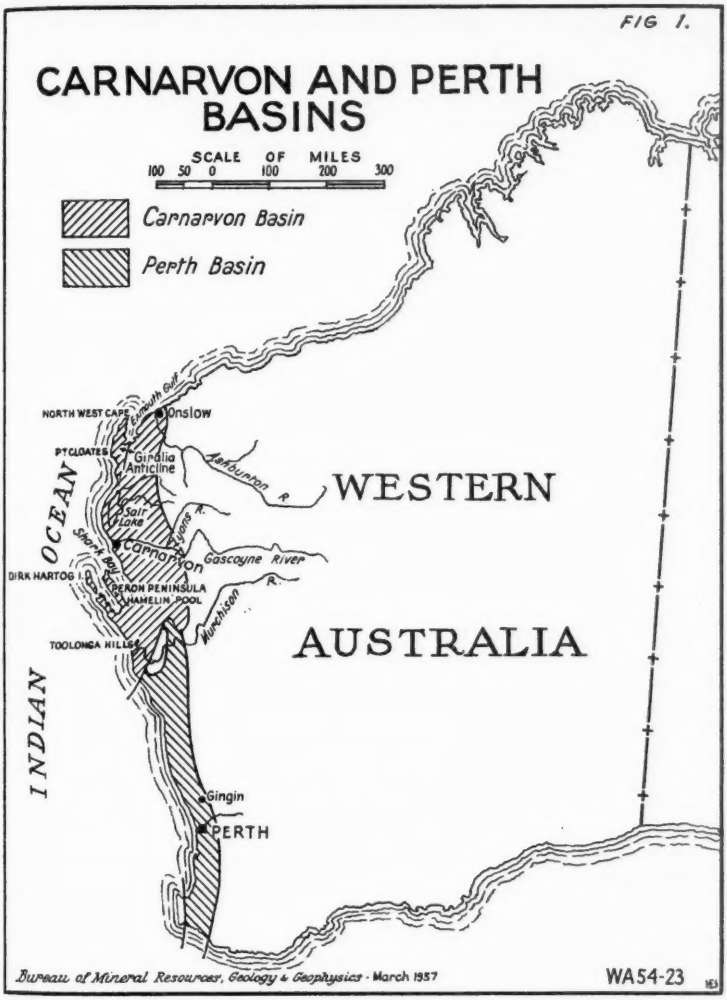

Fig. 1

Upper Cretaceous beds crop out in the lower Murchison River and Shark Bay areas. Clarke and Teichert (1948) investigated the Murchison River area; geologists of the Bureau of Mineral Resources and West Australian Petroleum Pty. Ltd. re-examined this area and also examined the Shark Bay area in 1954 (Johnstone, Condon and Playford, in press). In the Mur-

chison River area the sequence is similar to that of the Giralia Anticline, but is much thinner and without definite field evidence for disconformities. In the Shark Bay area, only calcilutite crops out; these outcrops and those of the Murchison River area are almost certainly continuous beneath a thin cover of sand and travertine. Upper Cretaceous beds occur in quarries between the two outcrop areas, and are also known from numerous water bores in which the same sequence and lithology have been observed.

In the Perth Basin the best known sequence is at Gingin (TEICHERT, 1947; FAIRBRIDGE, 1953). The lowermost unit exposed is a glauconitic sandstone, named by FAIRBRIDGE the Molecap Greensand; overlying this is the Gingin Chalk, slightly glauconitic at the base and top, and above this another glauconitic sandstone, named by FAIRBRIDGE the Poison Hill Greensand. In this section also there is no direct evidence of disconformities. The same sequence occurs at Dandaragan, except that the Molecap Greensand contains two phosphate beds; the beds in these two outcrop areas are probably continuous beneath a thin surface cover.

A deep bore at Pearce Aerodrome, and other bores in the Perth Metropolitan area, passed through unfossiliferous glauconitic sandstones, which lithologically have been correlated with the sandstone of the Gingin sequence (FAIRBRIDGE, 1953). No equivalent of the Gingin Chalk was observed in these bores.

Previous work

The Upper Cretaceous microfaunas of Western Australia have been investigated by several workers; the first was HOWCHIN, who in 1907 published a brief description of 37 species from the Gingin Chalk. A chart showing the range of these species as known at that time was published by GLAUERT in 1910. CHAPMAN (1917) published a more comprehensive paper on the fauna of the same formation, recording and figuring 134 species and varieties of foraminifera, and 20 species and varieties of ostracoda. CHAPMAN and CRESPIN (in RAGGATT, 1936) and CRESPIN (1938) gave lists of foraminiferal species identified from samples collected in the Giralia-Cardabia area, and commented on the age of the formations. EDGELL (1952; 1954; 1957) has examined the fauna of the beds of the Giralia Anticline. More recently, the writer (BELFORD, 1954) has examined outcrop and subsurface samples from the Murchison River and Shark Bay areas, and also samples of the Gingin Chalk. In addition, samples from several bores in the coastal part of the Carnarvon Basin have been examined by Miss CRESPIN and the writer for West Australian Petroleum Pty. Ltd. (see references). Dr. M. F. GLAESSNER of the University of Adelaide has also examined samples for this Company, and the writer has had the benefit of discussion with him. B. E. BALME has found spores of possible Upper Cretaceous age from water bores in the Perth Basin.

In all investigations of the Upper Cretaceous microfaunas of Western Australia, the foraminifera have received more attention than other groups. Ostracoda and radiolaria are often well preserved, but little work has been done on them.

Stratigraphy

In accordance with the standard division of the Cretaceous System (see Muller and Schenck, 1943) the boundary between the Lower and Upper Cretaceous in Western Australia is placed between the Albian and Cenomanian stages. European stage names have been used in subdividing the Upper Cretaceous beds of Western Australia in preference to introducing local names, as the succession of smaller foraminifera established in other parts of the world enables fairly exact stratigraphical determinations and inter-regional correlations to be made. The Upper Cretaceous foraminiferal fauna of Western Australia has affinities with those of both Europe and America.

The ages of the beds as determined from an examination of the foraminifera do not in all cases agree with those resulting from a study of the macro-fossils. Different workers who have examined the macro-fossils are also not always in agreement; this position is similar to that recently reported by Reiss (1956) from the Upper Cretaceous of Israel.

Cenomanian—Turonian

These two stages are treated together, as the assemblages examined by the writer do not give sufficient evidence to enable a boundary to be drawn between them.

Sedimentation was continuous from the Lower Cretaceous into the Upper Cretaceous, and at the beginning of Upper Cretaceous time the Gearle Siltstone was being deposited in the northern part of the Carnarvon Basin. In outcrop at the type locality, this formation has a thickness of 535 feet (Condon et al., 1956); at other places, lack of reliable dips and poor outcrop make measurement of the thickness difficult. Foraminifera are rare in outcrop samples, and arenaceous forms are dominant. Species recorded are *Ammobaculites fisheri* Crespin, *Ammodiscus* sp. cf. *A. cretaceus* (Reuss), *Trochamminoides* sp. cf. *T. coronus* Loeblich and Tappan, *Gaudryinella* sp. cf. *G. irregularis* Tappan, *Marssonella oxycona* (Reuss), *Textularia* sp. cf. *T. washitensis* Carsey, *Haplophragmoides* sp., and *Pelosina* sp. Radiolaria are common, with one band of abundant and well preserved specimens towards the top of the outcrop section. Forms identified are *Dictyomitra australis* Hinde, *Lithocampe fusiformis* Hinde, *Lithocyclia exilis* Hinde, *Cenosphaera* spp., *Spongodiscus* sp., *Saturnalis* sp., *Rhopalodictyum* sp., *Spongoprunum* sp., *Stylosphaera* sp., *Staurosphaera* sp., *Spongotribus* sp., and *Diacanthocapsa* sp. This assemblage contains species described by Hinde (1893) from Fanny Bay, Port Darwin, but is much richer.

The foraminiferal assemblage recorded by Edgell (1952) and by Condon et al. (1956) as from the top of the Gearle Siltstone is now known to be incorrectly placed. The sample in which this assemblage occurred was thought to be from the Gearle Siltstone but was later recognised to belong in the Korojon Calcarenite. It was this sample which caused Edgell to regard the upper beds of the Gearle Siltstone as Senonian (Campanian).

Subsurface sections of the Gearle Siltstone penetrated by bores on the Rough Range Structure are much thicker than any known from outcrop. A core taken in the lower part of this formation contained an assemblage of foraminifera not known from outcrop samples. Species recorded are *Globotruncana (Praeglobotruncana) delrioensis* (PLUMMER), *Neobulimina minima* TAPPAN, *Lenticulina gaultina* (BERTHELIN), *Anomalina petita* CARSEY, *Globigerina planispira* TAPPAN, *Bigenerina* sp. cf. *B. wintoni* LOEBLICH and TAPPAN, *Tristix excavata* (REUSS), *Trochammina* sp. cf. *T. depressa* LOZO, *T. minuta* CRESPIN, *Ammobaculites* sp. cf. *A. fisheri* CRESPIN, *Spiroplectammina cushmani* CRESPIN, *S. edgelli* CRESPIN and *Pelosina lagenoides* CRESPIN. Some of these species were described from the Lower Cretaceous deposits of the Great Artesian Basin (CRESPIN, 1953), and others occur in the Cretaceous of Texas. The assemblage indicates an Albian age for this sample from the Gearle Siltstone.

The Albian age of beds of the Gearle Siltstone well above the base of the formation in subsurface section makes it impossible to accept the suggested upper Albian or Cenomanian age for the underlying Windalia Radiolarite (EDGELL, 1952). This formation is at least lower Albian in age, and may even be of Aptian age. BRUNNSCHWEILER in CONDON et al. (1956), identified ammonites of the family Acanthoceratidae from this formation, and placed it in the Cenomanian. In a manuscript now in preparation, this author has corrected these identifications, and regards the formation as upper Aptian plus probably lower Albian in age, from the evidence of ammonites of the family Aconeceratidae.

Cores taken on the Rough Range Structure from the upper beds of the Gearle Siltstone also contain assemblages not known from outcrop. One core contained abundant specimens of *Globotruncana (Praeglobotruncana) stephani stephani* (GANDOLFI), *G. (P.) stephani* (GANDOLFI) *turbinata* (REICHEL), and very rare *G. (G.) helvetica* BOLLI. The species *Globotruncana stephani* was made the type species of the subgenus *Rotundina* SUBBOTINA, 1953 (see KÜPPER, 1955). KÜPPER (1956) placed *Rotundina* in the synonomy of the subgenus *Praeglobotruncana* BERMUDEZ 1952, which has as type species *Globorotalia delrioensis* PLUMMER. BRÖNNIMAN and BROWN (1955) placed *G. (P.) stephani stephani*, but not *(G. (P.) stephani turbinata*, in the synonomy of *G. (P.) delrioensis*. Benthonic forms were rare in this core; species recorded are *Anomalina* sp. cf. *A. petita* CARSEY, *Gaudryina cushmani* TAPPAN, *Spiroplectammina* sp. cf. *S. nuda* LALICKER, *Marssonella oxycona* (REUSS) and *Trochammina* sp.

The species *G. (P.) delrioensis*, as interpeted by BRÖNNIMAN and BROWN (1955), ranges from the upper Albian to the lower Turonian. The subspecies *turbinata* ranges from the Cenomanian to lower Turonian. KÜPPER (1955) states that although the absolute range of the subspecies *turbinata* is usually given as Cenomanian to lower Turonian, it is most abundant in the upper Cenomanian. A chart with this paper shows the subspecies restricted to the Cenomanian. MORNOD (1949) and HAGN and ZEIL (1954) give the range as Cenomanian—lower Turonian. *G. (G.) helvetica* also ranges from the upper Cenomanian to the lower Turonian (BOLLI, 1944; HAGN and ZEIL, 1954).

From the known stratigraphical range of the planktonic forms present, and the absence of any planktonic species known only from beds younger than Cenomanian, this assemblage from the upper part of the Gearle Siltstone is regarded as upper Cenomanian in age. This assemblage has been found only once, and was the first record of definite and stratigraphically restricted Upper Cretaceous foraminiferal species from the Gearle Siltstone.

Other equally important samples from the upper beds of the Gearle Siltstone, also taken in bores on the Rough Range Structure, contain a fauna which shows that deposition of this formation continued into the lower Turonian. These cores contain representatives of the *Globotruncana lapparenti group* [mainly *G. lapparenti* Brotzen *tricarinata* (Quereau)], *Globigerina cretacea* d'Orbigny, *Globigerinella aspera* (Ehrenberg), *Hastigerinella* sp. (cf. *subcretacea* Carsey), *Anomalina* sp. cf. *A. petita* Carsey, *Ammodiscus* sp. cf. *A. cretaceus* (Reuss) and also the forms *Bigenerina* sp. cf. *B. compressiuscula* Chapman, *Clavulinoides* sp. cf. *C. trilaterus* (Cushman), *Stensioina* sp., *Valvulineria* sp. and *Anomalinoides* spp. which previously have been known only from outcrop, in beds of Santonian age. One core also contained rare small specimes of *Globotruncana (Praeglobotruncana) delrioensis*. Published work (Hamilton, 1953; Hagn and Zeil, 1954; Bolli, 1951; Küpper, 1956) indicates that most of the planktonic species in these cores are not known to occur below the Turonian, while *G. (P.) delrioensis* is not known above the lower Turonian. This assemblage is therefore regarded as lower Turonian in age. Spores have been recorded from this horizon by Cookson (1956) who regards it as possibly Turonian.

The relationship between the outcrop and subsurface sections of the Gearle Siltstone in the area of the Giralia Anticline is not known. The fact that the Upper Cretaceous planktonic foraminifera occurring in the upper beds in subsurface section have never been recorded from outcrop suggests that the outcrop represents the lower part of the formation. This would agree with the field evidence of disconformity recorded by Condon et al. (1956) at the top of the Gearle Siltstone. Similar assemblages of arenaceous foraminifera occur both in outcrop and in the lower beds of subsurface sections. If this correlation is correct, it is probable that the outcrop beds of the Gearle Siltstone are of Lower and not Upper Cretaceous age. The problems of the exact position of the Lower Cretaceous-Upper Cretaceous boundary and the Cenomanian—Turonian boundary have not been solved. A boundary could be drawn between the Cenomanian and Turonian in this area if the vertical ranges of the planktonic species were accurately known. As they have not been recorded from outcrop in the Gearle Siltstone and as present sub-surface information is insufficient, this is not yet possible.

Other subsurface sections of the Gearle Siltstone, or of formations equivalent to the Gearle Siltstone, are known from bores in the Shark Bay area, the Pelican Hill and Brickhouse Bores near Carnarvon, and the Onslow

Bore. Arenaceous foraminifera are dominant in samples from all these bores. One specimen of *Rotalipora*, identified as *R.* cf. *turonica*, was recorded by EDGELL (1957) from the Cenomanian—Turonian beds of the Brickhouse Bore.

In the Murchison River section, the Alinga Greensand is probably to be placed in the Cenomanian—Turonian. Beds are much thinner than on the Giralia Anticline, and the foraminiferal faunas of the Gearle Siltstone are absent. Rare, poorly preserved radiolaria have been found, and also fish teeth. Belemnites occur in both the Alinga Greensand and the Gearle Siltstone, and form the main basis for a comparison between the two formations.

The Thirindine Formation underlying the Alinga Greensand contains very rare *Ammodiscus* sp., *Pelosina lagenoides*, *Haplophragmoides* sp., and abundant poorly preserved radiolaria, (*Dictyomitra australis*, *Cenosphaera* spp.). This formation is probably to be correlated with the Windalia Radiolarite, of Lower Cretaceous age.

The Molecap Greensand of the Gingin sequence may also have been deposited during the Cenomanian—Turonian. There is no field evidence of any break in deposition between this formation and the overlying Gingin Chalk; TEICHERT (1947) regarded the contact as gradational and conformable, and placed the Molecap Greensand in the Santonian. No microfossils are known from the formation; the only fossils found are plesiosaur and fish bones, fossil wood and a belemnite (*? Dimitobelus*). Lithologically, the Molecap Greensand is similar to the Alinga Greensand, and although both formations are poorly fossiliferous, and have only fish remains and belemnites in common, it is here suggested that they are approximate time equivalents. If this interpretation is correct there is a time-break between the Molecap Greensand and the overlying Gingin Chalk; some support is given to this suggestion by the absence of belemnites from formations above both the Gearle Siltstone and the Alinga Greensand, both of which are terminated by time-breaks.

During the Cenomanian and Lower Turonian, deposition occurred throughout much of the Carnarvon Basin. The greatest thickness of beds was deposited in the northern part of the basin, in the area of the present Rough Range and Cape Range Structures. In the Murchison River area the thickness is very small, either because disconformities are present in the section, but cannot be detected by field observation (except perhaps by abrupt changes in lithology), or because it was an area of continuous but very slow deposition.

An indication of the depositional environment may be obtained from a consideration of the faunal and mineral content of the beds. LOWMAN (1949) showed that assemblages dominated by *Haplophragmoides* and *Trochammina* are characteristic of brackish water marshes, or of marine environments with a low oxygen content, and stated (p. 1957) "*Haplophragmoides*, *Trochammina* and their associates tolerate bottom conditions that the normal assemblages do not tolerate". Arenaceous foraminifera

also seem to be more characteristic of cold water conditions (Glaessner, 1945, p. 100).

Glauconite is common in the Cenomanian—Turonian deposits of the Murchison River and Gingin sequences, but is rare in the Giralia Anticline. Cloud (1955), reviewing the literature dealing with the occurrences of this mineral, named many factors affecting its formation; amongst them are (a) at least slightly reducing conditions; (b) marine waters of normal salinity; (c) mainly in the neritic zone; (d) water probably not markedly warm; (e) slow rate of detrital influx.

Considering all these factors, it seems probable that the beds of the Murchison River and Gingin sequences were deposited in a near-shore environment, with a low hinterland giving very slow accumulation, and in a reducing environment too extreme to allow the development of a large benthonic fauna. With this interpretation, it is unnecessary to postulate disconformities to explain the small thickness of beds deposited. In the area of the present Rough Range and Cape Range structures, which was the main depositional area of the basin at this time, conditions were at first unfavourable to benthonic life, and the assemblages were dominated by planktonic forms. Later, conditions improved, probably to deep open clear water allowing a more varied fauna to exist.

After the deposition of the beds discussed above, and probably in lower Turonian time, a general regression began from the Carnarvon Basin and possibly also the Perth Basin. Deposition was resumed in the Perth Basin and the southern part of the Carnarvon Basin in middle Senonian time.

Senonian

(a) Santonian

The only known outcrops of beds of Santonian age are in the Perth Basin, near Gingin and Dandaragan (Gingin Chalk), and in the lower Murchison River area of the Carnarvon Basin, where the Toolonga Calcilutite was deposited. The Toolonga Calcilutite as now defined (Johnstone et al., in press) includes the Toolonga Chalk and Second Gully Shale of Clarke and Teichert (1948); it ranges in age from Santonian to Campanian. The age of the lower part of the Toolonga Calcilutite, and of the Gingin Chalk, is determined as Santonian by the occurrence in these formations of plates of the crinoid genera *Marsupites* and *Uintacrinus*, which enable a correlation with the *Marsupites* zone of the standard Cretaceous System. This correlation was first given by Withers in 1924, when he recorded the genus *Uintacrinus* in the Gingin Chalk, and then again in 1926, when the genus *Marsupites* was found.

Foraminiferal assemblages of the Gingin Chalk and the Toolonga Calcilutite are very similar. The change from the underlying beds is very abrupt; calcareous species predominate, but some large arenaceous species which are not known to occur above the Santonian are also present. These species are *Bigenerina compressiuscula* Chapman, *Goësella chapmani* Cushman, and *Clavulinoides* sp. cf. *C. trilaterus* (Cushman). Other arenaceous

species are *Dorothia* sp. cf. *D. bulletta* (CARSEY), *Verneuilina parri* CUSHMAN, *Marssonella oxycona* (REUSS) and *Spiroplectammina laevis* (ROEMER) var. *cretosa* CUSHMAN, all of which range throughout the Santonian beds. *Gaudryina* sp. cf. *G. laevigata* FRANKE occurs rarely. Globigerinidae and Globorotalidae are abundant. Species of *Globotruncana* recorded are *G. lapparenti lapparenti* BROTZEN, *G. lapparenti* BROTZEN *tricarinata* (QUEREAU), *G. lapparenti* BROTZEN *bulloides* VOGLER, *G. marginata* (REUSS), *G. ventricosa* WHITE, *G.* sp. aff. *G. concavata* (BROTZEN), and *G. globigerinoides* BROTZEN (the last species found at the base of the Santonian only). *Globotruncana spinea* KIKOINE was recorded by EDGELL (1957), from the Gingin Chalk. *Globigerina cretacea* D'ORBIGNY and *Globigerinella aspera* (EHRENBERG) are abundant. *Bolivinoides strigillata strigillata* (CHAPMAN) is common in the Gingin Chalk, and has been found at several localities in the Murchison River area. Papillate species of *Neoflabellina* are common, but the species cannot readily be identified. The specimens seem to fall into the groups of *N. deltoidea* WEDEKIND, *N. praerugosa* HILTERMANN and *N. rugosa* subspp. Buliminidae are rare and are represented only by *Bulimina reussi* MORROW and *B. parva* FRANKE. Several species of *Frondicularia* have been identified, such as *F. mucronata* REUSS, *F. teuria* FINLAY, *F. goldfussi* REUSS, *F. planifolium* CHAPMAN, *F. archiaciana* REUSS. Other lagenid genera such as *Robulus, Lenticulina, Marginulina, Saracenaria, Vaginulina, Dentalina,* and *Nodosaria* are well represented. *Cibicides excavata* BROTZEN, *Anomalina* sp. cf. *A. rubiginosa* CUSHMAN, *Cibicidoides* sp., *Valvulineria allomorphinoides* (REUSS), *Eouvigerina aculeata* (MARSSON), *Pullenia reussi* CUSHMAN and TODD, *Stensioina* sp. nov., *? Gavelinopsis* sp. nov., and *Anomalinoides* spp. also occur (the last three not known above the Santonian).

Bores in the Carnarvon Basin have extended the previously known area of occurrence of beds of Santonian age. Beds of this age have been penetrated in bores on the Grierson, Cape Cuvier, and Warroora Anticlines, in the Brickhouse Bores and the Pelican Hill Bore, both near Carnarvon, and in the Peron Peninsula No. 2 Bore. The area of the Warroora Anticline is the farthest north that beds of Santonian age have been recognised. The foraminifera from these beds are similar to those from outcrop; they include the large arenaceous species and also species of *Neoflabellina, Bolivinoides strigillata strigillata,* and *? Gavelinopsis* sp. nov. Ostracoda are abundant and well preserved in the Santonian and younger beds. Genera identified are *Cytherelloidea, Bairdia, Cythereis, Acanthocythere, Cytheridea, Paracypris, Brachycythere* and *Loxoconcha.*

In the Giralia Anticline, although the Korojon Calcarenite has been placed in the Santonian on macro-fossil evidence, no evidence of Santonian age is found in the foraminiferal assemblages.

(b) Campanian

In the Gingin sequence, the Poison Hill Greensand overlies the Gingin Chalk; no fossils have been found in this formation, and it is not possible to give any definite statement as to its age. Lithologically, the Poison Hill Greensand may be compared with the Boongerooda Greensand of the Car-

narvon Basin; this formation is regarded as Paleocene in age (Condon et al., 1956). Teichert (1947) placed the Poison Hill Greensand in the Campanian, and it is possible that most of the formation is of this age, although the upper beds may extend into the Maestrichtian, or even higher.

In the Murchison River area the depositional environment was unchanged, and the deposition of a calcilutite continued. Lithologically similar deposits of this age also crop out in the Shark Bay area near the Hamelin Telegraph Station, and on Yaringa North Station. Transgression occurred in the area of the Giralia Anticline during Campanian time, and the Korojon Calcarenite was deposited disconformably on the Gearle Siltstone.

A distinct faunal change occurs in the upper beds of the Toolonga Calcilutite, although several species continue from the underlying Santonian beds. The large arenaceous species of the Santonian are not present; of the Lagenindae, *Robulus* and *Lenticulina* are still abundant, but species of *Nodosaria, Dentalina,* and *Frondicularia* occur rarely. *Globotruncana* sp. cf. *G. arca* (Cushman) appears in addition to the species given above for the Santonian. *Spiroplectammina grzybowskii* Frizzell and *Palmula* cf. *P. pilulata* Cushman appear for the first time in this section. *Bolivinoides strigillata strigillata* has been found at one locality, at the base of the Campanian. Small papillate species of *Neoflabellina* occur rarely, and also *N.* sp. aff. *N. praereticulata* Hiltermann. *Globorotalites conicus* (Carsey) occurs commonly. Species ranging upwards from the Santonian are *Marssonella oxycona, Dorothia* sp. cf. *D. bulletta, Verneuilina parri, Valvulineria allomorphinoides, Eouvigerina aculeata, Anomalina* sp. cf. *A. rubiginosa,* and *Cibicides excavata.*

The beds of the Shark Bay area contain all the species recorded from the Campanian of the Murchison River section, with the exception that *Bolivinoides strigillata strigillata* has not been found.

In the Korojon Calcarenite of the Giralia Anticline, *Globotruncana arca* (Cushman) occurs throughout. Other species of *Globotruncana* identified are *G. paraventricosa* (Hofker), *G. lapparenti lapparenti, G. lapparenti* cf. *tricarinata, G. marginata, G. globigerinoides,* and *G. fornicata* Plummer. Other characteristic upper Senonian species also ranging throughout the formation are *Cibicides voltziana* (d'Orbigny) and *Bolivina incrassata* Reuss. Arenaceous species occurring throughout are *Spiroplectammina grzybowskii, S. laevis* var. *cretosa, Gaudryina laevigata, G. rugosa* d'Orbigny, *Verneuilina parri* and *Marssonella oxycona.* Lagenidae are abundant; species of *Frondicularia* recorded are *F. archiaciana, F. goldfussi, F. teuria,* and *F. inversa. Palmula* sp. cf. *P. pilulata* occurs rarely. *Bolivinoides* sp. cf. *B. decorata* (Jones) *delicatula* Cushman has been recorded towards the base of the formation in the Brickhouse No. 1 Bore, and *B. decorata australis* Edgell from the upper beds in outcrop (Edgell, 1954). *Neoflabellina praereticulata* Hiltermann is recorded from subsurface samples on the Rough Range Structure, and *N.* sp. cf. *N. numismalis* occurs in outcrop. *Stensiöina pommerana* Brotzen and *S.* sp. occur frequently throughout.

The Korojon Calcarenite is regarded by the writer, and also by Edgell

(1952), as mainly Campanian, with the uppermost beds extending into the Maestrichtian. In CONDON (1954) the age is given as Santonian, and in CONDON et al. (1956) as "Santonian but perhaps also early Campanian"; this age is repeated by GLENISTER, MILLER and FURNISH (1955, p. 494). The older age is based on cephalopoda found in the formation, and identified by R. O. BRUNNSCHWEILER. In the writer's opinion, the absence of the crinoid genera *Marsupites* and *Uintacrinus*, the absence of typical Santonian foraminifera, and the occurrence of upper Senonian forms such as *Globotruncana arca, Bolivina incrassata* and *Cibicides voltziana* leave no doubt as to the Campanian age of the Korojon Calcarenite.

Subsurface information has enlarged the area over which beds of Campanian age are known to occur. All bores on the Rough Range Structure, on the Grierson, Warroora, and Cape Cuvier Anticlines, Dirk Hartog Island and Peron Peninsula, and also the Onslow Bore, have passed through beds of Campanian age. The typical assemblage of the Korojon Calcarenite has been found in all these bores. The assemblage of the upper beds of the Toolonga Calcilutite occurs in samples from the Pelican Hill Bore.

Two biotopes may be recognised in the Campanian of the Carnarvon Basin; one is typified by the assemblage occurring in the beds of the Murchison River area and the other by the assemblage of the Korojon Calcarenite. The two assemblages have some species in common, but are easily distinguished by the species restricted to one or the other. *Bolivina incrassata, Cibicides voltziana, Globotruncana arca, Bolivinoides* sp. cf. *B. decorata delicatula, B. decorata australis, Stensiöina pommerana* and *Neoflabellina* sp. cf. *N. numismalis* occur in the Korojon Calcarenite, but not in the Toolonga Calcilutite. *Bolivinoides strigillata strigillata* and *Neoflabellina* sp. aff. *N. praereticulata* are known only from the Toolonga Calcilutite.

The faunal assemblage of the Korojon Calcarenite may be traced from the outcrop on the Giralia Anticline southward to subsurface sections on Dirk Hartog Island and Peron Peninsula, a distance of some 230 miles. The assemblage of the Toolonga Calcilutite is known over much the same distance, from outcrop in the lower Murchison River area to subsurface sections near Carnarvon. The uniformity of the faunas over such an area suggests that the Campanian beds of Western Australia were deposited in a shallow epicontinental sea, as on other continents; in these the faunas are known to have been remarkably uniform over wide areas.

The relationship of these two biotopes is important for both stratigraphy and palaeogeography. Some indication of the ages of the assemblages occurring in them may be obtained by considering the known vertical range of species common to the Upper Cretaceous of Australia and other parts of the world. Tables have been published showing the vertical distribution of some of these species in Europe. According to HILTERMANN (1953, tables 3 and 4) *Bolivina incrassata* and *Neoflabellina numismalis* are more characteristic of upper Campanian and Maestrichtian beds in north-west Germany. CUSHMAN (1946) records *Bolivina incrassata* from beds of Taylor and Navarro age, that is, Campanian and Maestrichtian. In north-west Germany,

Stensiöina pommerana occurs rarely at the top of the lower Campanian, but is more characteristic of the upper Campanian and lower Maestrichtian. Pozaryska (1954) shows this species occurring in the uppermost Campanian and Maestrichtian of Poland.

Little significance can be attached at present to the record of *Bolivinoides* sp. cf. *B. decorata delicatula* from the Upper Cretaceous of Western Australia. According to Hiltermann and Koch (1950) and Hiltermann (1953), *B. decorata delicatula* does not occur below the upper Campanian in north-west Germany. However, the form referred to this species by Hiltermann and Koch was placed by Reiss (1954) in *B. regularis* sp. nov. The form recorded by Edgell (1954) from the Upper Cretaceous of Western Australia is stated to be similar to specimens from the upper part of the lower Campanian and the basal upper Campanian of north-west Germany, and it has been suggested that they are primitive forms of *B. decorata delicatula* (Hiltermann, personal communication to Edgell). The taxonomic position of the Australian forms is uncertain; Edgell notes that they are not nearly so highly ornamented as forms referred to this subspecies by Hiltermann and Koch. They are possibly to be included in the group of poorly ornamented *Bolivinoides* such as *B. praecursor* and *B. laevigata;* specimens are very rare in the Upper Cretaceous of Western Australia, and none are available for examination. The most important point is the stratigraphical position of similar forms in the Upper Cretaceous of north-west Germany. Pozaryska (1954) recorded this species from the Upper Cretaceous of Poland, and showed its range as upper Santonian to Maestrichtian, but from her figure (p. 56, fig. 7) it is obvious that the Polish specimens, or at least those conspecific with the specimen figured, cannot be referred to this species. The species *Bolivinoides strigillata strigillata,* which occurs in the Toolonga Calcilutite, is not known to range above the lower Campanian.

In some bores both biotopes have been penetrated and this has given further evidence of the relationship between them. In the Brickhouse Station No. 1 Water Bore and the Pelican Hill Bore, Campanian assemblages occur below the fauna of the Korojon Calcarenite, and agree very closely with the fauna of the Murchison River section. The Santonian—Campanian beds in these bores are almost 1,000 feet thick. Isolated cores from other bores also contain a fauna of Campanian age, but the characteristic upper Senonian species of the Korojon Calcarenite are absent.

The available evidence is sufficient to indicate that these two biotopes contain successive fossil faunas and are not laterally equivalent. From the known distribution of some species in other areas the Korojon Calcarenite is regarded as most probably upper Campanian in age, and the upper beds of the Toolonga Calcilutite as lower Campanian. Although the differences between faunas of the two biotopes are distinct in outcrop samples, the change from one to the other is probably gradual. The thickness of the Campanian beds in subsurface section indicates that a large part of the section, over which the change could be traced, is not exposed; this gap in outcrop extends from the top of the Toolonga Calcilutite to the base of the

Korojon Calcarenite. The nature of the contact between the two biotopes would be known only if a complete subsurface section were available from those parts of the basin where deposition was continuous through the Upper Cretaceous.

The interpretation of the palaeogeography of this area is shown in figures 5 and 6. During the lower Campanian deposition occurred in the basin only along a narrow coastal strip from north of Carnarvon to south of the Murchison River. In the Perth Basin, positive evidence of deposition during lower Campanian time is lacking.

In the Murchison River and Shark Bay areas, there is no evidence of the deposition of beds younger than the lower Campanian. The top of the Toolonga Calcilutite throughout its outcrop area is an erosional surface and beds of upper Campanian age may have been removed. On Yaringa North Station beds of Eocene age overlie the Toolonga Calcilutite, and all that can be definitely stated is that regression and erosion occurred at some time between the lower Campanian and the Eocene. This regression may have begun at the beginning of upper Campanian time, together with the transgression in the north over the area of the present Giralia Anticline. The suggested upper Campanian shoreline is drawn along the known limits of beds of this age; further information, particularly in the Murchison River and Shark Bay areas, may make it necessary to move this shoreline to the east.

Maestrichtian

No outcrops of Maestrichtian age are known from the Murchison River or Shark Bay areas. In the Giralia Anticline, deposition of the Korojon Calcarenite continued. The Maestrichtian age of the uppermost beds of this formation is based on the occurrence of such species as *Bolivinoides draco draco* (Marsson), *Neoflabellina reticulata* (Reuss), *Bolivinoides decorata* (Jones) *gigantea* Hiltermann and Koch, and *Pseudotextularia varians* Rzehak. The Maestrichtian species of *Globotruncana* which occur in the overlying Miria Marl have not been found in the Korojon Calcarenite. The species *Neoflabellina reticulata* has been regarded as an index fossil for Maestrichtian age (Reiss, 1952; Pozaryska, 1954). Hiltermann (1954) showed this species occurring in the uppermost Campanian of north-west Germany, but has since (1956) modified his table 5 to restrict it to the Maestrichtian. Cushman (1946) records the species from the upper part of the Taylor Marl and from beds of Navarro age, that is upper Campanian and Maestrichtian. *Bolivinoides draco draco* was also recorded by Hiltermann (1953) from the uppermost Campanian, but is now (1956) restricted to the Maestrichtian; it does not occur below the Maestrichtian of Poland. *B. decorata gigantea* and *Pseudotextularia varians* are not known to occur in beds older than Maestrichtian.

After the deposition of the Korojon Calcarenite, the sea withdrew, probably in lower Maestrichtian times, and this was followed by an erosional interval. There was then a further transgression, and the Miria Marl was deposited disconformably on the Korojon Calcarenite; the area of the pre-

FIG 2
EXTENT OF UPPER CRETACEOUS DEPOSITS
Outcrops
Concealed
FIG 3
FIG 4
SUGGESTED
FIG 5
FIG 6
SHORELINES
FIG 7
FIG 8
CENOMANIAN-LOWER TURONIAN
Outcrops
Bores
SANTONIAN
Outcrops
Bores
LOWER CAMPANIAN
Outcrops
Bores
UPPER CAMPANIAN
Outcrops
Bores
MAESTRICHTIAN (PRE-MIRIA MARL)
Outcrop
Bores
MAESTRICHTIAN (MIRIA MARL)
Outcrops
WA54-24 KS

Fig. 2—8

sent Giralia Anticline is the only known area of outcrop of deposits of this transgression. CONDON et al. (1956, p. 68), on macrofossil evidence, consider this disconformity to represent non-deposition in lower and middle Campanian times.

In addition to the Maestrichtian species occurring in the Korojon Calcarenite, the Miria Marl contains *Globotruncana stuarti* (DE LAPPARENT), *C. citae* BOLLI, *G. contusa* (CUSHMAN), *G. lugeoni* TILEV, *G. elevata elevata* BROTZEN, *G. planata* EDGELL, and *Coleites* sp. Species ranging upward

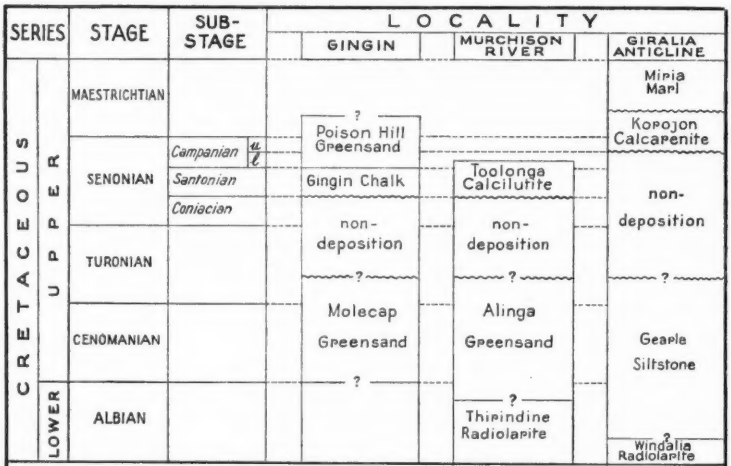

Fig. 9

from the Campanian are *Bolivina incrassata, Cibicides voltziana* and *Globotruncana arca.*

Beds of Maestrichtian age, containing the same fauna as the uppermost beds of the Korojon Calcarenite, have been penetrated in bores on Cape Cuvier Anticline, Dirk Hartog Island, Peron Peninsula, and in the Pelican Hill Bore, near Carnarvon. Geologists of West Australian Petroleum Pty. Ltd. regard this part of the section in Dirk Hartog Island as Toolonga Calcilutite (letter dated May, 6th, 1957).

On macro-fossil evidence, SPATH (1940) regarded the Miria Marl as lower Maestrichtian in age, with possibly some late Campanian. BRUNNSCHWEILER (in CONDON et al., 1956) recognised two successive, partly overlapping assemblages, one upper Campanian and the other lower Maestrichtian.

The suggested shore-lines for both periods of deposition in the Maestrichtian are shown in figures 7 and 8. Deposition in the Perth Basin again cannot be demonstrated.

It is difficult to reach any reliable conclusions on the ecology of the Santonian, Campanian and Maestrichtian assemblages. There was evidently a strong open-water influence, and the frequent abundance of rotaliid species may indicate the middle neritic zone as the environment of deposition (Lowman 1949). The necessary quantitative work to determine the proportion of planktonic species has not been done, but as Bandy (1951) has pointed out, the distribution of these forms could be affected by currents, and therefore be of little significance.

Conclusion

The interpretations given above, based on present knowledge of the foraminiferal faunas, may have to be revised in the future, particularly as a result of further subsurface investigations. Much more work remains to be done on the Upper Cretaceous micro-faunas of Western Australia, particularly in the description and figuring of the faunas, and in determining more accurately the range of significant species. When this is done it will be possible to zone the beds more closely, and to make more exact correlations, and the value of the foraminifera to the stratigraphy of Western Australia will be greatly increased.

References

Bandy, O. L., 1951: Upper Cretaceous foraminifera from the Carlsbad area, San Diego county, California. J. Paleont., **25** (4), 488—513. — Bolli, H., 1944: Zur Stratigraphie der Oberen Kreide in den höheren helvetischen Decken. Ecl. geol. Helv., **37** (2), 218—328. — Bolli, H., 1951: The genus Globotruncana in Trinidad, B.W.I. J. Paleont., **25** (2), 187—199. — Brönniman, P., and Brown, N. K., 1955: Taxonomy of the Globotruncanidae. Ecl. geol. Helv., **48** (2), 503—561. — Brunnschweiler, R. O.: New Aconeceratidae (Ammonoidea) from the Aptian and Albian of Australia. Bur. Min. Resour. Aust. Rep. **38** (in preparation). — Chapman, F., 1917: Monograph of the foraminifera and ostracoda of the Gingin Chalk. Bull. geol. Surv. W. Aust. **72.** — Clarke, E. de C., and Teichert, C., 1948: Cretaceous stratigraphy of the Lower Murchison River area. J. roy. Soc. W. Aust., **32,** 19—47. — Cloud, P. E. Jr., 1955: Physical limits of glauconite formation. Bull. Amer. Ass. Petrol. Geol., **39** (4), 484—492. — Condon, M. A., 1954: Progress Report on the stratigraphy and structure of the Carnarvon Basin, Western Australia. Bur. Min. Resour. Aust. Rep. **15.** — Condon, M. A., Johnstone, D., Prichard, C. E., and Johnstone, M. H., 1956: The Giralia and Marrilla Anticlines, North West Division, Western Australia. Bur. Min. Resour. Aust. Bull. **25.** — Cookson, Isabel C., 1956: Additional microplankton from Australian late Mesozoic and Tertiary sediments. Aust. J. Marine Freshwater Res. 7 (1), 183—191. — Crespin, Irene, 1938: Upper Cretaceous foraminifera from the North-West Basin, Western Australia. J. Paleont., **12,** 391—395. — Crespin, Irene, 1953: Lower Cretaceous foraminifera from the Great Artesian Basin, Australia. Contr. Cushman Fdn, **4** (1), 26—36. — Crespin, Irene, and Belford, D. J., 1954: Tertiary and Mesozoic stratigraphy and micropalaeontology of Rough Range No. 1 Bore, Carnarvon Basin, Western Australia. Bur. Min. Resour. Aust. Rec. **1954**/18 (unpublished). — Crespin, Irene, 1956: Stratigraphy and micropalaeontology of Cape Range No. 1 Bore, Carnarvon Basin, Western Australia. Ibid., **1956**/40

(unpublished). — CRESPIN, Irene, 1956: Micropalaeontological examinatioun of cores from Rough Range No. 4 Bore, Carnarvon Basin Western Australia. Ibid., **1956**/54 (unpublished). — CRESPIN, Irene, 1956: Micropalaeontological examination of samples from Rough Range South No. 1 Bore, Carnarvon Basin, Western Australia. Ibid., **1956**/104. — CUSHMAN, J. A., 1946: Upper Cretaceous foraminifera of the Gulf Coastal region of the United States and adjacent areas. Prof. Pap. U.S. geol. Surv. **206.** — EDGELL, H. S., 1952: The micropalaeontology of the Giralia Anticline, N.W. Australia. Bur. Min. Resour. Aust. Rec. **1952**/75 (unpublished). — EDGELL, H. S., 1954: The stratigraphical value of Bolivinoides in the Upper Cretaceous of North-West Australia. Contr. Cushman Fdn, **5** (2), 68—76. — EDGELL, H. S., 1957: The genus Globotruncana in Northwest Australia. Micropalaeontology, **3** (2), 101—126. — FAIRBRIDGE, R. W., 1953: Australian Stratigraphy. Perth, Univ. of W. Aust. — FRIZZELL, D. L., 1954: Handbook of Cretaceous foraminifera of Texas. Univ. Texas. Bur. econ. Geol., Rep. Inv. **22.** — GLAESSNER, M. F., 1945: Principles of Micropalaeontology. Melbourne, Univ. of Melbourne Press. — GLAUERT, L., 1910: A list of Western Australian fossils systematically arranged. Bull. geol. Surv. W. Aust. **36.** — GLENISTER, B. F., MILLER, A. K., and FURNISH, W. M., 1956: Upper Cretaceous and early Tertiary nautiloids from Western Australia. J. Palaeont., **30** (3), 492—503. — HAGN, H., and ZEIL, W., 1954: Globotruncanen aus dem Ober-Cenoman und Unter-Turon der Bayerischen Alpen. Ecl. geol. Helv., **47** (1), 1—60. — HAMILTON, E. L., 1953: Upper Cretaceous, Tertiary and Recent planktonic foraminifera from mid-Pacific flat-topped sea-mounts. J. Palaeont., **27** (2), 204—237. — HILTERMANN, H., 1953: Stratigraphische Fragen des Campan und Maastricht unter besonderer Berücksichtigung der Mikropaläontologie. Geol. Jb., **67,** 47—66. — HILTERMANN, H., 1956: Biostratigraphie der Oberkreide auf Grund von Mikrofossilien. Paläont. Z., **30,** 19—32. — HILTERMANN, H., and KOCH, W., 1950: Taxonomie und Vertikalverbreitung von Bolivinoides — Arten im Senon Nordwestdeutschlands. Geol. Jb., **64,** 595—632. — HINDE, C. J., 1893: Note on a radiolarian rock from Fanny Bay, Port Darwin. Quart. J. geol. Soc. Lond., **49,** 221—226. — HOWCHIN, W., 1907: Foraminifera from a calcareous marlstone, Gingin. Bull. geol. Surv. W. Aust. **27.** — JOHNSTONE, D., CONDON, M. A., and PLAYFORD, P. E.: The Stratigraphy of the Lower Murchison River area and North Yaringa Station, Western Australia. J. roy. Soc. W. Aust. (in press). — KÜPPER, K., 1955: Upper Cretaceous foraminifera from the "Franciscan Series" New Almaden district California. Contr. Cushman Fdn, **6** (3), 112—118. — KÜPPER, K., 1956: Upper Cretaceous pélagic foraminifera from the "Antelope Shale", Glenn and Calusa Counties, California. Ibid., **7** (2), 40—47. — LOWMAN, S. W., 1949: Sedimentary facies in Gulf Coast. Bull. Amer. Ass. Petrol. Geol., **33** (12), 1939—1997. — MORNOD, L., 1949: Les Globorotalidés du Crétacé supérieur du Montsalvens (Préalpes fribourgeoises). Ecl. geol. Helv., **42** (2), 573—596. — MULLER, S. W., and SCHENCK, H. G., 1943: Standard of Cretaceous System. Bull. Amer. Assoc. Petrol. Geol. **27** (3), 262—278. — POZARYSKA, K., 1954: The Upper Cretaceous index foraminifera from Central Poland. Acta geol. polon., **4,** 249—276. (Polish with English and Russian summaries). — RAGGATT, H. G., 1936: Geology of the North-west Basin, Western Australia. J. roy. Soc. N.S.W. **70** (1), 100—174. — REISS, Z., 1952: On the Upper Cretaceous and Lower Tertiary micro-faunas of Israel. Bull. Res. Coun. Israel, **2** (1), 37—50. — REISS, Z., 1954: Upper Cretaceous and Lower Tertiary Bolivinoides from Israel. Contr. Cushman Fdn, **5** (4), 154—164. — REISS, Z., 1956: Remarks on the age of some late Cretaceous and early Tertiary stratigraphic units in Israel. Bull. Res. Coun. Israel, **5 B** (1), 121—126. — SPATH, L. F., 1940: On Upper Cretaceous (Maestrichtian) ammonoidea from Western Australia.

J. roy. Soc. W. Aust., **26**, 41—58. — Teichert, C., 1947: Stratigraphy of Western Australia. Bull. Amer. Ass. Petrol. Geol., **31**, 1—70. — Withers, T. H., 1924: The occurrence of the crinoid Uintacrinus in Australia. J. roy. Soc. W. Aust., **11** (2), 15—18. — Withers, T. H., 1926: The crinoid Marsupites in the Upper Cretaceous of Western Australia. Ibid., **12** (11), 97—104.

THE STRUCTURE OF NEW ZEALAND FROM SEISMIC EVIDENCE

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With 7 Figures

Summary

The New Zealand region is characterised by a crust 20—25 kms in thickness, and a sub-crust extending to at least 370 kms. These are separated by a transition layer extending from the base of the crust to a depth of about 100 kms. The crust is divided into blocks by steeply dipping faults. Some blocks are seismically active and others stable. The region is bounded by the Pacific Basin to the east, and the Tasman Basin to the west. Both of these areas have oceanic crusts about 5 kms thick. The sub-crust is traversed by a major wedge-shaped structure within which the deep focus seismicity is confined. This has been named the "Sub-Crustal Rift", and its activity is apparently an extension of that associated with the Kermadec Trench. It follows a roughly south-west course from the Bay of Plenty to Farewell Spit, when it turns abruptly south-south-east, and finishes close to the Alpine Fault. Faults with both north-east and north-west trends are at present active. The most important of the north-west faults appears to run through Cook Strait. It is considered that the main crustal faults could have developed as the result of successive positioning above the Sub-Crustal Rift. Stable blocks have not been fractured in this way. There is some evidence for a difference in crustal structure on opposite sides of the Rift. The western portion is about 5 kms thicker, and contains a layer in which the P-velocities exceed 7 km/sec. No velocities above $6^1/_2$ km/sec have been observed in the eastern part. There is no evidence of arcuate structure. All the crustal and sub-crustal features appear to follow linear trends.

Introduction

Most of the seismologists who have discussed the structure of New Zealand restrict themselves to a consideration of the crust, that is to say, to the material above the Mohorovičić discontinuity. The primary purpose of this paper is to make structural deductions from the distribution and nature of seismic activity in New Zealand, and only secondarily to refer to the problem of "crustal structure" as that term is generally understood. Bullen (1936, 1938 a, 1938 b, 1939), Officer (1955) and the writer (Eiby, 1957) have estimated the thickness of the crust and discussed its constitution on the basis of crustal pulses in natural earthquake records, surface-wave dispersion, and explosion records respectively. Hayes (1943, 1953 a) has given particular attention to the pattern of deep-focus

seismicity in New Zealand. Unfortunately, the fullest exposition of his findings (HAYES, 1950 a) has had only limited circulation in mimeographed form.

The reliance which can be placed upon seismic data necessarily depends upon the number and distribution of seismograph stations in the area. Stations of the New Zealand network have been shown in the sketch map (Fig. 7), together with the other geographical names to which reference is made in the text. With the exception of Auckland, which has a Milne-Shaw seismograph, all the stations shown have instruments with periods of approximately one second, magnifications of 1500 to 3000, and timing accurate to at least half a second. In addition to the stations shown, there are a number of second order stations with strong motion instruments only.

It is appreciated that the final structural picture must also include a full account of other geophysical and geological data. At present there are a number of apparent conflicts, and it should be emphasised that seismology is essentially concerned with present happenings. It is perhaps less able than geology to distinguish long continuing trends.

The Seismicity of New Zealand

From general consideration of geology, it is evident that New Zealand does not form an unbroken structural unit. The high seismicity of most of the country is evidence of extensive active faulting; and the distribution of earthquake foci allows the limits of the active area to be defined. HAYES (1953 a) has published a series of maps showing the epicentres determined at the Seismological Observatory in Wellington, classified according to focal depth and magnitude. These cover the period 1940—1947 inclusive. Subsequent activity has been published in the form of annual lists and maps (HAYES, 1948, 1949, 1950 b, 1952, 1953 a, 1953 b, 1953 c, 1955). During this period, only the Wairarapa earthquake of 1942 June 24 has reached magnitude 7, so that the picture is not unduly distorted by large clusters of aftershocks, and may be regarded as typical of minor activity at the present time.

HAYES (1953 a) has studied the sixteen largest earthquakes since European occupation of the country, and assigned them approximate epicentres and magnitudes, all greater than about 7. Nearly half of these have been accompanied by observed surface movement on faults, and several others can be assigned to known faults with reasonable certainty. No complete study of Recent faulting in New Zealand exists, but WELLMAN (1953) has given detailed information about the South Island, and published a small-scale map of the whole country (1955). On the whole this picture bears out the Californian experience (GUTENBERG and RICHTER, 1954, p. 89) that there is little tendency for the smaller shocks to align themselves with the major faults, which appear to be responsible for the largest shocks only. Certain orderly alignments of the minor activity, however, can be found; and these have been indicated in Fig. 1, 2, and 3.

Fig. 1 is based on shallow and normal shocks; that is to say, those within the crust or close to its base. An attempt has been made to indicate the density of epicentres in the different regions by shading. The trend lines are in general characterised by a rise in the seismicity as the line is approached from the shaded side, followed by a marked drop or even complete cessation as the line is crossed. On the whole, seismic activity

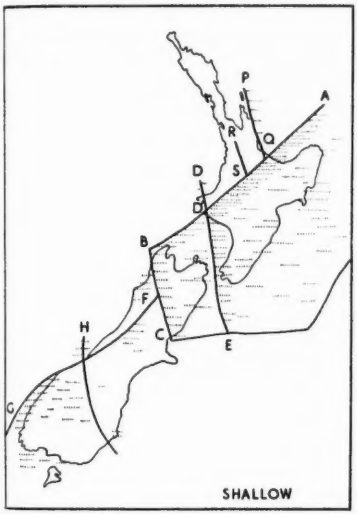

Fig. 1

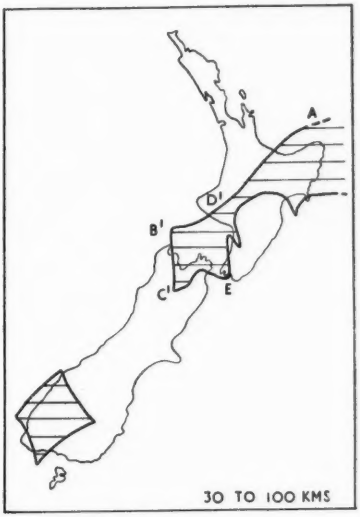

Fig. 2

Fig. 1. Distribution of Shallow Earthquakes. The shading gives a rough indication of the density of epicentres. For explanation of letters see text.

Fig. 2. Distribution of Earthquakes with Focal Depths between 30 and 100 kilometres.

appears greater on the north side of north-west trends, and on the south side of north-east trends.

Fig. 2 shows the activity between about 30 kms and 100 kms. This appears to be a zone of transition between the shallow activity and that at greater depths, which is shown in Fig. 3. The limiting depth of seismic activity in New Zealand is normally taken to be about 370 kms, but an exceptional earthquake was recorded on 1953 March 24. Its epicentre is 38.95° S, 174.5° E, and its focal depth 580 kms. These values are taken from an unpublished paper by M. G. Muir.

It appears from these patterns that the New Zealand structure can be divided into three layers — the crust, a transition zone, and a subcrust. Although certain features are common to all three patterns, the

great differences in the shape and extent of the active regions shows that in a number of respects they may act as mechanically independent systems. This appears to have an important bearing upon the regional stress pattern.

a) North-Easterly Trends

It is clear from WELLMAN's fault map (1955) and from the direction of the principal mountain chains that a north-easterly trend governs the structure of much of the country. The most prominent manifestation of this trend in the seismicity pattern is bounded to the west by the line AB, which appears in Fig. 1, 2, and 3. It runs from the central Bay of Plenty to West Nelson, and extends almost vertically to the limiting depth of earthquake activity. This depth is slightly greater at the northern end. Although the 580 km shock lies on or close to the line, the absence of similar shocks along other parts of the trend makes it doubtful whether it is justifiable to extend the feature to this depth over its whole length. The eastern side of the active zone dips less steeply, and is not well defined at depths of less than 100 km.

The existence of this structure, which has been named the Sub-Crustal Rift, is confirmed by a number of other observations. The writer has already drawn attention to certain peculiarities in the isoseismal pattern of earthquakes whose felt area includes or abuts upon the Rift (EIBY, 1955 a). These can be explained if the Rift, or the faulted region of the crust above it, is a strong reflector or absorber of seismic energy. Instrumental recordings at Onerahi, Karapiro, and to a lesser degree at New Plymouth seem to confirm this interpretation. The waveform of earthquakes recorded from the region east of it is usually simpler, shorter in duration, and longer in period. P-waves are relatively unaffected, but S-waves are considerably reduced in amplitude, and may be represented as only a single pulse or cycle. The regional gravity anomaly pattern on the two sides of the Rift is markedly different. The gradient is low on the north-west side, and abnormally high on the southeast. At the same time, the direction of strike of the anomaly contours undergoes a change. Further evidence is found in the structural trends of the surface geology. Those to the south-east lie parallel to the Rift, whilst those to the north-west appear to be cut off by it. In a paper presented to the 1957 conference of the Australian and New Zealand Association for the Advancement of Science, R. R. DIBBLE has established that the Rift marks a separation between regions of different P_n and S_n velocity, those to the south-east being abnormally high. The writer has also found some confirmation of abnormally high P-velocities along the Rift in a preliminary study of the P-residuals given in the International Seismological Summary for shallow earthquakes at distances up to 30° from Wellington.

The most prominent South Island feature is the Alpine Fault, FG (Fig. 1). Like the Sub-Crustal Rift, it marks the western boundary of seismic activity, the only exception being a small group of epicentres near the point H. It is however purely a crustal feature so far as seismic evi-

dence is concerned, and consequently of less structural importance than the Rift. The number of epicentres along the Alpine Fault is much smaller than that of those bounded by the North Island feature, and there may even be a complete break in the activity at about the latitude of Banks Peninsula. There is some evidence from the renewed activity at depths up to 100 km in the Southland region that the fault extends into the transition zone. However, there are no first-class seismographs south of

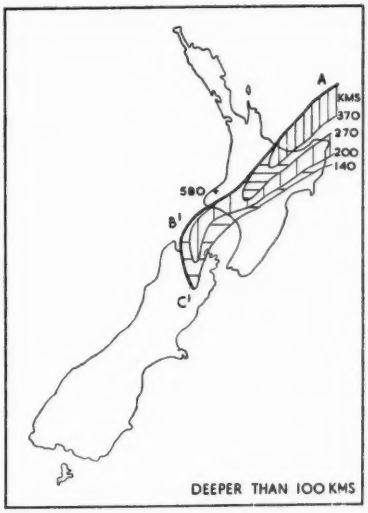

Fig. 3. Distribution of Earthquakes with Focal Depths greater than 100 kilometres.

those at Christchurch and Kaimata, so that control of depth and of the east-west location of epicentres is poor in this region. Other interpretations of the seismicity are therefore possible. The main evidence for deep foci in this region comes from the isoseismal patterns.

b) North-Westerly Trends

In the northern part of the South Island, the Sub-Crustal Rift undergoes a marked change in direction, the new strike being south or south-south-east (see Fig. 3). This change extends to the transition region, but not in any simple way to the crust, though there is reasonable evidence that the line BC marks a southern limit to the activity in the Nelson area, and perhaps a northern limit to the seismic significance of the Alpine Fault. Unlike the north-east striking portion, the boundary of this part of the Rift is not vertical, but appears to dip to the north-north-east at an angle of about 60°. It appears likely from the present data that the

southerly extremity terminates at the Alpine Fault, but this is not completely certain.

There is a marked alignment of epicentres along DE, Fig. 1, which runs from a point north of New Plymouth through Cook Strait to the northern flank of the Chatham Rise in about latitude 42° S. This line intersects the Rift in a point D′, very close to the volcanic Mount Egmont. Judged on the density of epicentres this is the crustal feature next in importance to that above the Rift. It is certainly more pronounced than the Alpine Fault.

Two other features having this trend are to be found in the North Island. Both lie on the north-western side of the Rift, and do not continue across it. The more active of these is that marked PQ in Fig. 1, which follows the line of the Coromandel Peninsula to a point slightly to the north of Great Barrier Island. The line RS is marked by numerous earthquakes of very small magnitude. Its northern end is close to Karapiro, and its general trend is that of the Waikato River.

The South Island picture is less clear, largely as a consequence of the lower accuracy of the epicentres in the far south. Isolated earthquakes appear in most parts of Eastern Otago, but the accuracy with which the epicentres are located is low, and the activity does not extend northwards to the Canterbury Plains. A boundary line with a general northwest strike can therefore be run southwards from the small group of epicentres at H on the opposite side of the Alpine Fault. This line also defines the northern limit of the 100 km activity.

c) Stable Blocks

The seismically stable region to the west of New Zealand includes not only the Tasman Basin and the Lord Howe Rise, but parts of Auckland and Northland. Its eastern boundary has already been discussed by the writer (Eiby, 1955 a). To the east of the country, the situation is less clear. The Chatham Rise and Campbell Plateau are stable, but off the North Island there are numerous epicentres extending to at least the 2,000 metre depth contour, which follows the trend of the Kermadec Trench.

d) Significance of the Trend Lines

The occurence of an earthquake is evidence of the existence of a fault, although in the majority of cases there is no surface trace to prove it. The focus of the shock may be related to an existing fault in two ways. Either the failure takes place at some point on the extent of the fault at which the opposite sides have become locked or cemented; or it takes place at one end of a fault which is in the process of increasing its extent.

The lines AB and FG, following the Sub-Crustal Rift and the Alpine Fault respectively, do not terminate in the region under consideration. The first becomes associated with the activity parallelling the Kermadec Trench, and the second with that extending southwards towards Macquarie Island. The transverse north-westerly trends, however, appear to extend as cracks of limited extent into an otherwise stable block. Ander-

son (1951) has shown that once an active fault exists, further activity tends to take place at an extremity. This is well shown by the distribution of aftershocks in the Kern County Earthquakes in California (Richter, 1955). In the present case, the transverse features appear to terminate in earthquake swarms, which have been quite active at both New Plymouth and Great Barrier Island. Those near Karapiro have been less intense, though the shocks have not been appreciably less numerous.

It is consequently concluded that these crustal trends represent active faults. The one parallelling the Sub-Crustal Rift and that through Cook Strait are the most important.

Sub-Crustal Structure

It is usual to consider deep-focus seismic activity as if it were disposed along an inclined plane, having certain ordered relationships to other geological and geophysical features, such as ocean trenches, gravity anomalies, and volcanism (Gutenberg and Richter, 1954, pp. 28, 29, 103, 104). Benioff (1954, 1955) has considered the seismicity of the Tonga and Kermadec regions from this point of view, and considers it to be basically a consequence of a great "oceanic fault" extending to a depth of some 700 kms. Fig. 4 combines the results of Hayes and Benioff to give a composite section of the whole region. Hayes (1950 a) gives some additional profiles, but since they are not normal to the trend of the activity, they are less useful.

In the Tonga region, Benioff shows the foci to lie between two parallel planes, some 300 kms apart, and dipping away from the Pacific Basin at an angle of approximately 58°. In the Kermadec case, however, he is content to show a single trend line inclined at 64°. In fact the arrangement has become wedge-shaped, the western side being inclined at 77° and the eastern at about 50°. The eastern slope remains reasonably constant in the profiles illustrated by Hayes, being 53°, 67°, and 62° in the three cases. The western side, however, undergoes a marked change. A trend dipping towards the Pacific appears, and the angle of dip, measured in the same sense, increases to 110°. This becomes more nearly vertical to the south-west, the angles in the two remaining cases being 103° and 94°. At the same time, the feature becomes narrower, the width in the central North Island being not more than 120—130 kms. At depths greater than 100 km, the Rift becomes narrower still, averaging about 50—60 km.

The Rift may consequently be pictured as a great wedge-shaped feature, extending south-west from the Kermadec region and crossing the North Island to the region of the South Taranaki Bight. There it undergoes an abrupt change of direction, and runs south-south-east. The western side of the Rift extends into the crust along the north-east trend, but the change in trend and the eastern side are only indirectly expressed in the crust.

Both the shape of the activity in Fig. 2 and the evidence of the profiles in Fig. 4 indicate a structural boundary at a depth of the order of 100 kms.

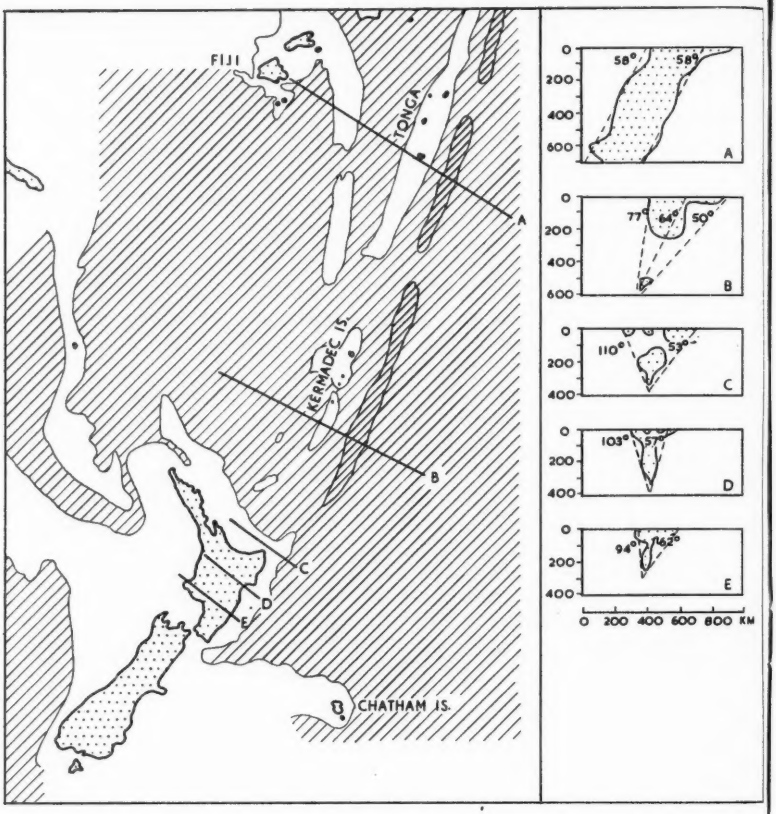

Fig. 4. Relationship of the Sub-Crustal Rift to the Tonga and Kermadec Trenches. Cross sections A and B after BENIOFF; C, D, and E after HAYES.

This does not appear to coincide with any of the accepted sharp discontinuities in the mantle, but could be related to the axis of GUTENBERG's low velocity "asthenosphere channel" (GUTENBERG and RICHTER, 1939; GUTENBERG, 1954), which marks a change in the elastic properties. Earthquake foci in the layer between this boundary and the base of the crust are limited to the west and to the south by the Sub-Crustal Rift. The eastern boundary of the active region is more irregular. There are two main areas of activity, one in the Cook Strait region and the other in the Gisborne-East Cape District. Only a narrow line of epicentres above the Rift links these two active regions. The considerable broadening of the active area in the Gisborne-East Cape region probably extends eastwards

to the Trench. The trend line D'E of Fig. 1 finds a counterpart in Fig. 2, as a roughly defined northern limit to the Cook Strait activity. Reference has already been made to activity at this depth in Southland. It does not appear to be connected with that in the north.

Crustal Structure

a) Explosion and Surface Wave Studies

The most detailed information about crustal structure in any part of New Zealand is that obtained from explosions in Wellington Harbour (Eiby, 1957). The interpretation of the refraction profile is adequately confirmed by reflections. A more general picture of the region is given by surface-wave studies (Officer, 1955). From these it is clear that the whole of the land area of New Zealand north of Banks Peninsula, together with the Lord Howe Rise, and the East Cape-Kermadec-Tonga Ridge has a crustal thickness of 20 to 25 kms. This is presumably also true of the rest of the South Island, the Chatham Rise, and the Campbell Plateau, for which no measurements are available. It is sharply differentiated from the 5 to 10 km crustal thickness found not only in the Pacific Basin, but also in the Tasman Basin to the west. The Fiji Basin has an intermediate thickness of the order of 15 kms.

The Wellington Profile established that the crust in the southern part of the North Island is definitely a layered structure. The sharpest velocity change is at a depth of only two kilometres, but its significance is at present believed to be physical rather than geological. A further boundary at a depth of about ten kilometres apparently marks the boundary between the "granitic" and "intermediate" layers of classical seismology; but the velocity of 6.22 km/sec assigned to the intermediate layer is lower than the values normally quoted for this layer.

As a preliminary to the Wellington Profile, reflection measurements were made near Auckland in the area to the west of the Hauraki Gulf. These have been prepared for publication by Mr. N. Modriniak of the Geophysical Survey, who has kindly allowed me to see them in advance. The Mohorovičić discontinuity is at 23 km, about 5 km greater than the Wellington value. There is also a marked discontinuity at 11 km. Above it, the velocity distributions in the two places are similar, but below it the velocities are much higher in the Hauraki region, reaching 7 to 7.5 km/sec. Except in thickness, this structure conforms reasonably to the classical "continental" type, which is not true of the Wellington area. It is considered that the boundary between these two types of structure follows the Sub-Crustal Rift; and this view is confirmed by the gravity evidence.

A series of reflection measurements across the Tonga Trench has been made by Raitt, Fisher, and Mason (1955). One of the three soundings obtained by them lies on each side of the trench, and the third is on its axis. They show certain similarities to the New Zealand results, and all five sections have therefore been shown in Fig. 5. The increase in the depth of the Mohorovičić discontinuity from its oceanic value occurs to

the east of the Trench, in a distance of 50 km or less. West of the Trench, under the Tofua Trough, it was not recorded, but it was considered that its depth must be at least 18 kms. No evidence was found for the existence of any considerable thickness of sialic material with velocities of the order of 6 km/sec. These results complement the value of 25 km assigned by OFFICER (1955) to the thickness of the crust along the East Cape-Kermadec Ridge.

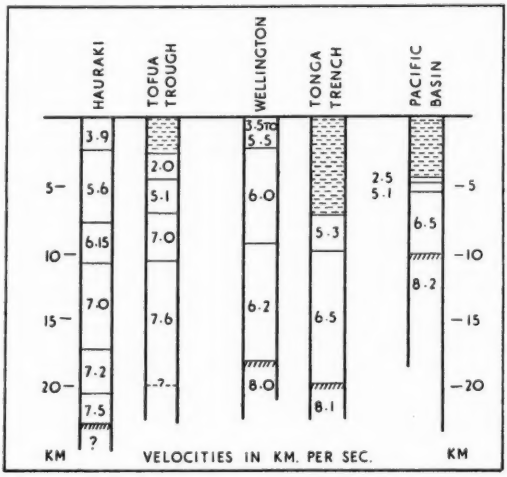

Fig. 5. Crustal Structure Measurements in the South West Pacific.

b) Natural Earthquake Studies

The attempt to use natural earthquake records for refraction studies of the crust in New Zealand has not had a success commensurate with the effort which has been applied to it. A number of earthquakes have been examined in detail, but few of the results have been published. The classical work of BULLEN (1939) which has been most widely quoted, is based largely upon a single shock in the Gisborne-Wairoa area.

The writer has studied two more recent shocks in some detail, and it is hoped to publish the details later. The first of these is the Cheviot Earthquake of 1951 January 10, and the other the Bay of Plenty Earthquake of 1956 January 30. From the Cheviot shock, the following values were obtained for the velocity of the principal phases.

P_n	7.9 ± 0.2 km/sec	S_n	4.50 ± 0.07 km/sec
P^*	6.4 ± 0.26 km/sec	S^*	3.57 ± 0.04 km/sec
P_g	5.63 ± 0.05 km/sec	S_g	2.7 ± 0.2 km/sec

There is also some evidence for a pulse with a velocity of 4.18 ± 0.12 km per sec, but the values must in all cases be considered provisional. They

are reasonably concordant with the results of the Wellington Profile, but the standard errors are high when the number of stations and the excellent timing available are considered. The Bay of Plenty Earthquake, although apparently well recorded, cannot be made to yield a uniform set of velocities, even for P arrivals. In the past it has been usual to dismiss such results as the consequence of station timing errors, but the methods now in use show that this cannot be the case, and that early records may have been unjustly denigrated.

In the course of routine epicentre determination, Mr. R. R. Dibble has graphed the arrival times of a considerable number of New Zealand earthquakes. The great majority of these shows a similar lack of consistency in both the behaviour of the pulses in a single earthquake, and in the velocities which can be assigned to the pulses in the different earthquakes. Even the P_n velocity varies widely above and below the 8 km/sec value considered to be "normal".

As far as any generalisation appears to be possible, the principal cause of anomalous behaviour is the Sub-Crustal Rift; or more probably, its expression in crustal features, which can be inferred from Fig. 1. The travel time of any ray which crosses this boundary is affected to a greater or less extent, whilst those that do not approximate to normality. It can therefore be understood that the Gisborne-Wairoa and Cheviot shocks would show a relatively normal behaviour, whilst the Bay of Plenty shock, with an epicentre at 36.9° S 117.1° E, almost directly above the Rift, is strongly anomalous.

It would appear from these results that there is a substantial area of the South West Pacific with a crustal thickness of 18 to 25 kilometres, almost completely surrounded by regions of true "oceanic" structure. The greater part of this area can reasonably be assigned a structure of the type which the writer has elsewhere defined as "insular" (Eiby, 1957). In the past, this region has commonly been termed "continental" on the basis of its relationship to the Andesite Line; but it is certain that at least those parts of the region which lie to the east of the Sub-Crustal Rift show marked differences in composition as well as in thickness from those of the classical continental crust. To the west of the Rift, further observations are needed. There is some indication that the crust there is slightly thicker, and perhaps closer to the continental type, though not identical with it.

Regional Stress

Now that a pattern of crustal and sub-crustal blocks has been deduced from the seismic evidence, it is interesting to examine the problem of the forces acting upon them. One method of approach is to examine the distribution of compressions and dilatations recorded as the initial impulse at different seismograph stations. The writer has made a limited study of this kind (Eiby, 1955 b). In order to apply the methods used in that paper, it is necessary to assume that the faults in the region are approximately parallel, and tend to undergo displacement in the same sense.

Emphasis was placed upon the tendency of the major faults to strike north-east, and it was concluded that they were undergoing clockwise transcurrent displacements. The present paper has established the importance of a trend approximately perpendicular to this, which probably predominates in much of the minor activity. In order to produce the same pattern of compressions and dilatations, the movements on these faults would have to be anticlockwise. ANDERSON (1951) has shown that such a system of faults at right angles can result from a single principal stress at an angle of approximately 45° to the fault. Seismic evidence is unable to distinguish between the two types of faulting, but leads unambiguously to a single direction of principal stress, approximately east-west. This is of course the stress direction responsible for the original fracture. In the case of subsequent earthquakes, it is sufficient for the stress to have a component of great enough magnitude to enlarge the fracture or to displace the blocks it separates. This may well be less than that needed to initiate a new fracture, and it should not be assumed without further proof that the direction of principal stress has remained unchanged.

Although a geologist would probably regard the north-east trend as predominant, and the major part of the Sub-Crustal Rift has this strike, the alignment of epicentres points to the existence of a fault system striking north-west, the most active member of which runs through Cook Strait. It is not clear which way this fault dips, as it does not seem necessary for a crustal feature to be at present continuous with a sub-crustal one to which it has at some time been related. Presumably both the Cook Strait Fault and the White Creek Fault, which produced the Murchison Earthquake of 1929, are crustal manifestations of the southern transverse branch of the Sub-Crustal Rift but were formed at different times. The horizontal component of displacement on the White Creek Fault is stated by WELLMAN (1953) to be anticlockwise, which is in agreement with the principal stress inferred above.

The seismic evidence therefore leads to the position illustrated in Fig. 6. Two stable blocks are separated by a zone of intense faulting. The major north-easterly feature represented by the Alpine Fault together with the crustal expression of the Sub-Crustal Rift is dislocated in the region of Cook Strait by a displacement of the southern part to the south-east. This displacement appears to have taken place in several stages, and to have affected the whole of the block BCED′ (Fig. 1). The large transcurrent movements postulated by WELLMAN from his studies of the Alpine Fault, and supported by BRODIE (1952) from the evidence of submarine topography must be interpreted as a movement of the crust, and perhaps the transition layer lying between the base of the crust and a depth of 100 kms. The development of crustal faulting can then be considered as the result of positional relationship to the Sub-Crustal Rift. As a consequence of crustal movement, new sections of the crust have lain above it in succession, developing a series of corresponding crustal features. It may be of some significance that the zone now overlying the Rift in the North

Island corresponds broadly with Wellman's "zone of normal faulting", the transcurrent faults all lying to the east of the Rift proper.

Benioff (1949, 1954) has suggested that the Tonga-Kermadec feature can be explained as the result of the meeting of a continental mass with an oceanic one of greater density. As a result of differences in hydrostatic pressure on the two sides of the boundary, a differential stress comes into existence, causing the continental material to flow over the oceanic at

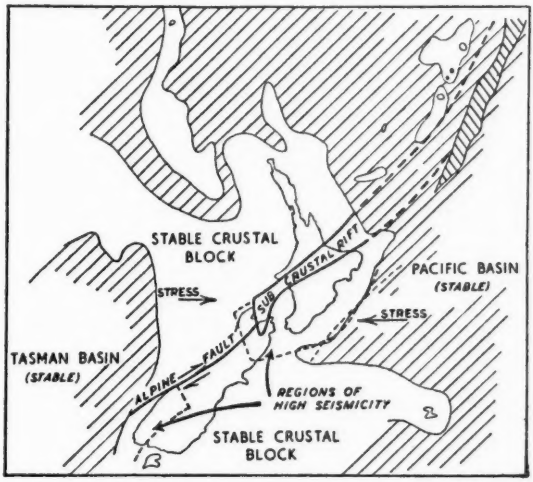

Fig. 6. Stable Blocks and Regional Stresses.

shallow depths, whilst at great ones, the oceanic material is forced beneath the continental mass. The contact thus becomes a great inclined fault. This picture does not appear to explain all the features of the Rift, in particular the change of trend and of dip in the Cook Strait region, and the tendency to become wedge-shaped; but it may be possible to modify it satisfactorily by making suitable assumptions about the original boundary of the continental material.

The exact relationship between the movement of the crustal features and the development of the Sub-Crustal Rift apparently depends upon the depth at which the maximum stresses are exerted.

Conclusions

New Zealand forms part of an extensive area of the southwest Pacific with an average crustal thickness slightly greater than 20 kms. The region is divided into blocks whose boundaries have been largely determined by a major feature which has been named the Sub-Crustal Rift. This forms

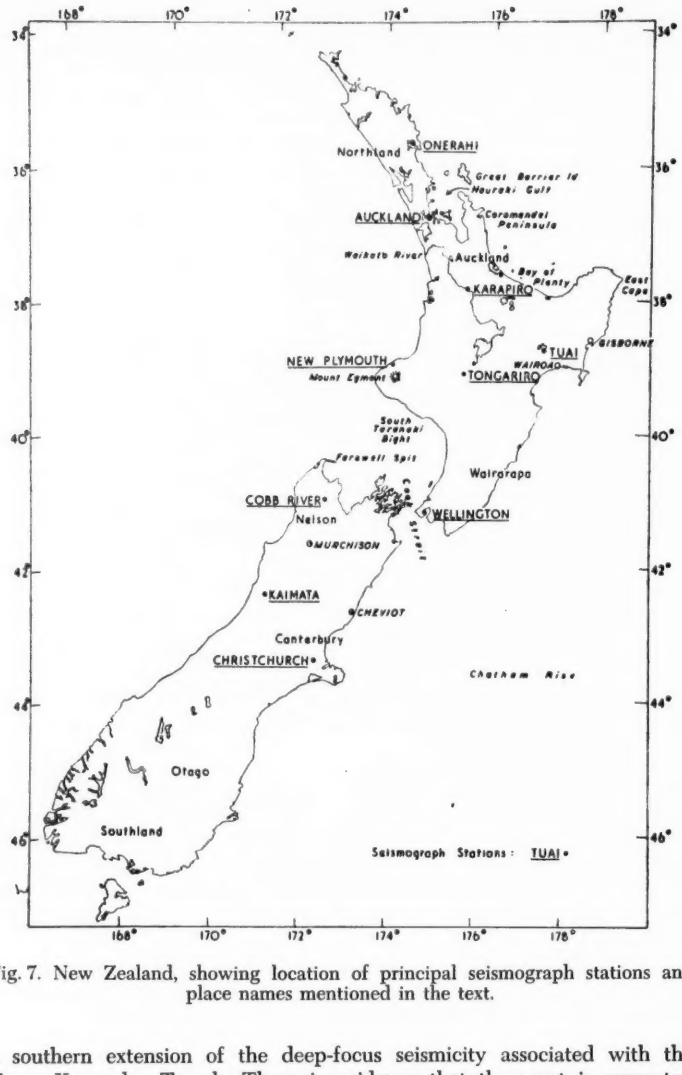

Fig. 7. New Zealand, showing location of principal seismograph stations and place names mentioned in the text.

a southern extension of the deep-focus seismicity associated with the Tonga-Kermadec Trench. There is evidence that the crust is separated from the true sub-crust by an intermediate zone extending to a depth of about 100 kms. The whole system appears to consist of essentially linear elements, and gives no evidence of arcuate trends of the kind suggested by MacPherson (1946). There is apparently some difference in crustal

structure on opposite sides of the Rift. To the south-east, this is of an insular type; to the north-west it has some features in common with continental crusts, but is thinner than usual. It is realised that the seismic picture differs at a number of points from that inferred from geological and other evidence. The problem should now be considered as a whole, bearing in mind that seismology may offer a glimpse of a chapter of geology that is still being written.

References

Anderson, E. M., 1951: The Dynamics of Faulting and Dyke Formation with Applications to Britain. Oliver and Boyd. Edinburgh, London (2nd edition). — Benioff, H., 1949: Seismic Evidence for the Fault Origin of Oceanic Deeps. Bulletin Geological Society America 60, p. 1837. – 1954: Orogenesis and Deep Crustal Structure — Additional Evidence from Seismology. Bulletin Geological Society America 65, p. 385. – 1955: Seismic Evidence for Crustal Structure and Tectonic Activity. Geological Society America Special Paper 62, p. 61. — Brodie, J. W., 1952: Features of the Sea Floor West of New Zealand. N.Z. J. Sci. Techn. B 33, p. 373; N.Z. Oceanographic Committee, Publication No. 7. — Bullen, K. E., 1936: On Near Earthquakes in the Vicinity of New Zealand. N.Z. J. Sci. Tech., 18, p. 493; Dom. Obs. Bull. 113. – 1938 a: The Phase S* in New Zealand Earthquakes. N.Z. J. Sci. Tech., 19, p. 519; Dom. Obs. Bull. 131. – 1938 b: The Wairoa Earthquake of 1932 Sept. 15. N.Z. J. Sci. Tech., 20, p. 31 B; Dom. Obs. Bull. 136. – 1939: The Crustal Structure of the New Zealand Region as Inferred from the Study of Seismic Waves. Proc. 6th Pacific Sci. Congress, p. 103. — Eiby, G. A., 1955 a: The Seismicity of Auckland City and Northland. N.Z. J. Sci. Tech., B 36, p. 488; Seis. Obs. Bull. S-100. – 1955 b: The Direction of Fault Movement in New Zealand. N.Z. J. Sci. Tech., B 36, p. 552; Seis. Obs. Bull. S-101. – 1957: Crustal Structure Project: The Wellington Profile. N.Z. D.S.I.R. Geophysical Memoir No. 5. — Gutenberg, B., 1954: Low Velocity Layers in the Earth's Mantle. Bull. Geological Soc. America, 65, p. 337. — Gutenberg, B., and Richter, C. F., 1939: New Evidence for a Change in Physical Conditions at Depths near 100 kms. Bull. Seismol. Soc. America, 29, p. 531. – 1954: Seismicity of the Earth and Associated Phenomena. Princeton University Press. 2nd Edition. — Hayes, R. C., 1943: The Sub-Crustal Structure in the New Zealand Region from Seismic Data. Bull. Seismol. Soc. America, 33, p. 75. – 1948: Earthquakes in New Zealand during the year 1947. N.Z. J. Sci. Tech., B 30, p. 102; Seis. Obs. Bull. S-90. – 1949: Earthquakes in New Zealand during the year 1948. N.Z. J. Sci. Tech., B 31, p. (1) 37; Seis. Obs. Bull. S-91. – 1950 a: Sub-Crustal Activity in New Zealand and its Relation to Surface Features. N.Z. Geophysical Conference 1950. Paper No. 9 (mimeographed). – 1950 b: Earthquake Origins in New Zealand during the year 1949. N.Z. J. Sci. Tech., B 31, p. (4) 43; Seis. Obs. Bull. S-92. – 1952: Earthquake Origins in New Zealand during the year 1950. N.Z. J. Sci. Tech., B 33, p. 305; Seis. Obs. Bull. S-96. – 1953 a: Some Aspects of Earthquake Activity in the New Zealand Region. Proc. 7th Pacific Science Congress, 2, p. 629. – 1953 b: Earthquake Origins in New Zealand during the year 1951. N.Z. J. Sci. Tech., B 34, p. 252; Seis. Obs. Bull. S-97. – 1953 c: Earthquake Origins in New Zealand during the year 1952. Seismological Observatory Bulletin S-98. – 1955: Earthquakes in New Zealand during the year 1953. Seismological Observatory Bulletin S-99. — MacPherson, E. O., 1946: An Outline of Late Cretaceous and Tertiary Diastrophism in New Zealand. N.Z. Geological Survey Memoir No. 6. — Offi-

CER, C. B., 1955: Southwest Pacific Crustal Structure. Trans. American Geophysical Union 36, p. 449. — RAITT, R. W., FISHER, R. L., and MASON, R. G., 1955: Tonga Trench. Geological Soc. America Special Paper 62, p. 237. — RICHTER, C. F., 1955: Foreshocks and Aftershocks. State of California Dept. of Natural Resources, Division of Mines, Bulletin No. 171, "Earthquakes in Kern County California during 1952", Par II, No. 9, p. 177. — WELLMAN, H. W., 1953: Data for the Study of Recent and Late Pleistocene Faulting in the South Island of New Zealand. N.Z. J. Sci. Tech., B 34, p. 270. – 1955: New Zealand Quarternary Tectonics. Geologische Rundschau 43 (1), p. 248—257.

STRUCTURAL SIGNIFICANCE OF SEA-FLOOR FEATURES AROUND NEW ZEALAND*)

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With 2 Figures

Summary

The oceanic highs and deeps around New Zealand exhibit a marked linearity and fall into three groups whose features trend NW—SE, E—W and NNE—SSW. These groups are recognized as structural provinces — the Northwestern, Chatham and Kermadec Provinces respectively, with both age and geographic differences.

The New Zealand land mass occupies a position at the meeting of the three structural trends and the relief is taken to be a function of this conjunction of trends.

No signs of late structural activity along trends referable to the Northwestern and Chatham provinces have been observed in New Zealand, and the submarine relief could be of pre-Tertiary age.

Active movement on the Kermadec province trend has taken place up to Recent time and the submarine features of this region are considerably younger.

Introduction

A large number of echo-soundings have been obtained in recent years in the Southwest Pacific Ocean and Tasman Sea. From these and pre-existing data a new bathymetric chart of the seas around New Zealand has been constructed (Fig. 1). Detailed bathymetry has previously been available for interpretation, only for portions of the area (FLEMING 1951, FLEMING & REED 1951, BRODIE 1952), and much new information has since been secured for these areas.

Bathymetry

The sea-floor around New Zealand does not fall away simply from the continental shelf edge to oceanic depths but is broken into a complex

*) New Zealand Oceanographic Institute Contribution No. 24.

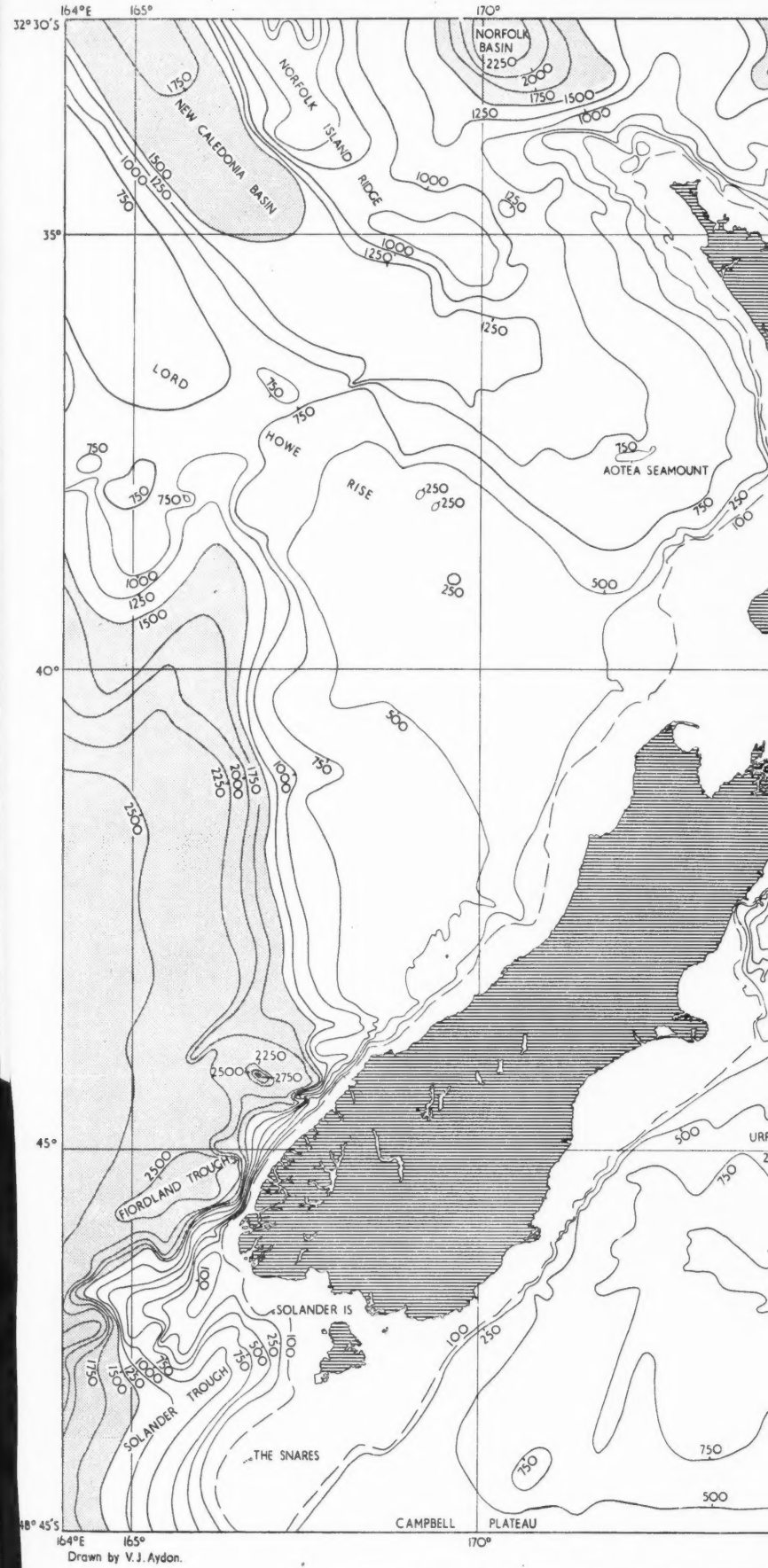
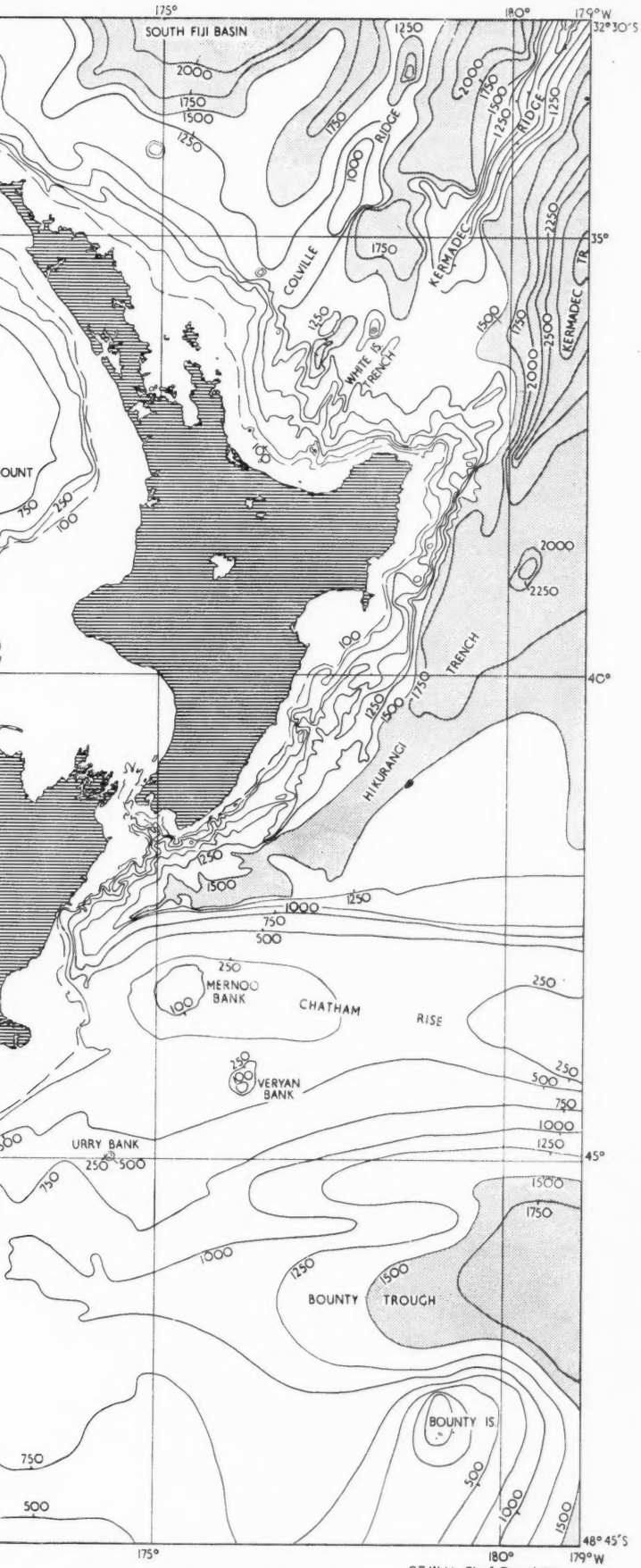


Fig. 1. Bathymetric chart of the sea-floor around New Zealand.



C.T. Webb Chief Draughtsman.

ew Zealand. (Isobaths at 250 fathom intervals).

pattern of oceanic highs and deeps. Within 300 miles of the coastline these deeps extend on the average, down to 2000 fathoms.

The bordering highs and deeps exhibit a marked linearity of trend and fall into three well-marked groups. The features west of New Zealand (Norfolk Basin, Norfolk Island Ridge, New Caledonia Basin and Lord Howe Rise) trend northwest to southeast: the highs and deeps east of New Zealand and south of Cook Strait (Chatham Rise, Bounty Trough and Campbell Plateau) trend east to west; those off the east coast north of Cook Strait and those off the southwest extremity of the South Island trend north-north-east to south-south-west.

The three groups of similarly trending highs and deeps can conveniently be named Northwestern (NW—SE), Chatham (E—W) and Kermadec (NNE—SSW) groups respectively. As well as distinctive orientations, other marked morphological differences are apparent.

In the Northwestern and Chatham groups width of highs and deeps across the strike is 100 miles or more, and both cover extensive areas of sea-floor. In the Kermadec group on the other hand, individual features are approximately fifty miles in width and the extent across the strike is considerably less than in either of the other two groups.

The Chatham Rise and Lord Howe Rise at their terminations against the New Zealand land mass are both broad elevations of the sea-floor with a relief above the flanking deeps of 1500 fathoms and a width of approximately 200 miles. The cross section of Chatham Rise is asymmetrical, the northern flank being more regular and scarp-like than the southern. Campbell Plateau is an extensive platform with less elongate form, approximately 400 miles wide. Norfolk Island Ridge is only 100 miles wide and has the same elevation as the two rises and Campbell Plateau above the adjoining deeps, the crests of all four highs lying in less than 500 fathoms.

Off the eastern coast, Bounty Trough, a broad depression, lies between the Bounty and Chatham Islands and forms the northern margin of the Campbell Plateau. New Caledonia Basin, west of the North Island lies between Norfolk Island Ridge and Lord Howe Rise. Its width is approximately 100 miles.

The remaining features, those of the Kermadec group occur in two areas. Those that lie off the northeastern and eastern coasts of the North Island — Colville Ridge, White Island Trench, Kermadec Ridge and Kermadec Trench are morphological analogues of the features to the north — Volcanic Ridge, Tofua Trough, Tonga Ridge and Tonga Trench — described by Raitt, Fisher and Mason (1955). Hikurangi Trench borders the east coast from East Cape to Banks Peninsula.

South and west of the southwestern extremity of the South Island, lies the second area dominated by a NNE—SSW orientation. Here, a low-relief depression of the Tasman Basin, the Fiordland Trough, parallels the west coast for 150 miles and extends a similar distance further south. Solander Trough indents the shelf between Solander and Stewart Islands. As yet ill-defined, this deep is roughly 50 miles wide and is at least 100 miles long.

Correlation of morphology with structure

When the scale of these morphological features is considered, their significance as structural units is undoubted. Within each of the three groups of features there is a striking uniformity of trend and it is thus possible to consider each group of similarly trending sea-floor features as constituting a structural province. Oceanic boundaries can thus be drawn between a Northwestern Province (trend NW—SE), Chatham Province (E—W) and Kermadec Province (NNE—SSW) (Fig. 2). These provinces represent structural units of the same order of magnitude: for example, the bulk of relief above the general ocean floor level of each of the two highs, Lord Howe Rise and Chatham Rise, is comparable with the amount of depression below the general level exhibited by the Kermadec Trench.

New Zealand structure

A number of syntheses of New Zealand structural history have been advanced. Among the later contributions, those of Wellman (1957), Lillie (1951) and Macpherson (1946), illustrate strikingly the variability of structural trends within individual phases of folding. Lillie emphasises the dominance in the structural plan of late Tertiary-early Pleistocene (Kaikoura) NE—NNE folds but points out that north-west strikes occur locally and suggests that posthumous folding has in part controlled these trends. He considers the dominant trend of the late Mesozoic (post-Hokonui) folding to have been NW. Macpherson (1946) put forward the hypothesis of late-Cretaceous and Tertiary folding occurring along a recurved arc, to reconcile his mapping of a swing in fold trend from NW in south and north of New Zealand through NE in the central area.

Wellman (1957) has mapped fold directions and related tectonic features of late Tertiary and Early Quaternary and fold directions of pre-Cretaceous rocks in the South Island. Both NE and NW elements dominate the structural pattern in each case.

The E—W elements in New Zealand structure are not prominent and can be recognized only at the eastern extremities of the North Island (in Cretaceous volcanics) at East Cape and in the Mesozoic Southland syncline in the South Island.

These and other writers are in part concerned with problems of the various structural phases and successively preponderant fold directions. These problems arise from the persistence from probable pre-Cambrian and early Paleozoic times to the present, of the same structural elements in the New Zealand region.

The age of oceanic structures

A number of the oceanic structures are reflected in similar features ashore. The Solander Trough lies on the same NNE line as the Tertiary Waiau Syncline: the line of the Bounty Trough can be extended westward to meet the axis of the Mesozoic Southland syncline: the Taupo Graben

(Pliocene—Pleistocene) continues ashore the line of the White Island Trench depression (Fleming, 1952). From these considerations the sea-floor features could well be of different ages and some may have persisted from pre-Tertiary times. On the other hand, all three trends are represented by major morphological units now present in the sea-floor relief. No evidence has been found ashore for late structural activity on trends referable to the Northwestern and Chatham provinces. Kermadec Trench on the other hand has dominated the structural scene since late Tertiary time

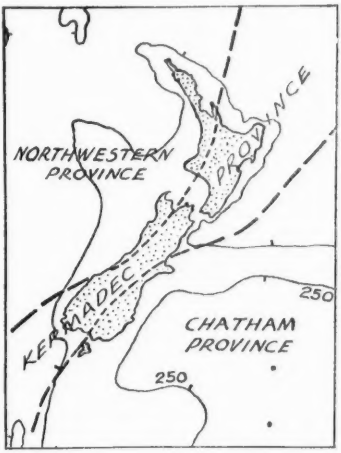


Fig. 2. Structural provinces of the New Zealand region.

and the NW and EW trending submarine features may thus be relict from at least early Tertiary time.

As suggested previously (Brodie, 1952) the Northwestern and Chatham features may have been formerly continuous and thus the same age and have later undergone dislocation by NNE trending transcurrent faulting.

Structural province boundaries

The oceanic features define the broad structural provinces; several groups of data define their boundaries that lie within the area of New Zealand.

Wellman (1954) has shown that for the northwestern portion of the North Island, a zone of southwesterly directed principal horizontal stress extends from North Cape to a line from Bay of Plenty to Cook Strait. The NNE-oriented transcurrent faults of the eastern portion of the North Island and in the South Island result from a principal horizontal stress directed on the average a few degrees south of west. Earthquake epicentres recorded by Hayes (1941, 1953) lie in two aligned NE trending zones —

one in the southwest corner of the South Island, the other extending from northern South Island across Cook Strait to the Bay of Plenty. EIBY (1955) has shown the North Auckland Peninsula to be aseismic.

The main tectonic feature in New Zealand, the Alpine Fault, extends from southwestern South Island to Cook Strait.

The boundaries of the three structural provinces can thus be drawn as shown in Figure 2.

Unpublished gravity and crustal structure data obtained by Geophysics Division of the Department of Scientific and Industrial Research, show that gravity anomaly trends fit the pattern of structural regions as developed here, and suggest that deep-seated structural differences in the crust might underlie the Kermadec and Northwestern provinces.

The most significant effect of this extension of the province boundaries is the linking of the Northern and Southern portions of the Kermadec Province. Viewed more broadly, there is continuity of expression of the present Kermadec trend from Samoa to south of New Zealand. While in the north the structural pattern is one of oceanic trench and ridge, this is succeeded southward by a minor trench and the land mass of the North Island of New Zealand; and southward again by the South Island land mass, interrupted by major transcurrent faulting and flanked on the west by a minor marginal trough in the deep floor of the Tasman Sea.

Relation of New Zealand to oceanic structures

If the static picture of existing evidence of structural deformation is considered, then a number of relationships, both broad and particular, between New Zealand and the oceanic structures can be determined.

In general terms, the area of the New Zealand land mass occupies a position at the geographic conjunction of the three major structural trends. The existence of New Zealand as a land mass can be taken as a function of this boundary position.

Tertiary and post-Tertiary structural and tectonic deformation observable in New Zealand is not necessarily representative of, and probably exceeds the deformation that has taken place in comparable time in the offshore areas. The oceanic features can better be taken as the regional structural norms.

Irrespective of possible differences in age of deformation, the New Zealand structural pattern should likewise be an expression of the three separate trends and of their interaction.

While there can be no doubt that the Kermadec trend, with its active NNE-oriented faults is dynamically the most significant at present, yet the evidence of the oceanic features, supported by geophysical data shows that in their respective regions the Northwestern and Chatham trends are dominant if not active.

The structural provinces

The significance of the structural provinces can be recapitulated.

The three oceanic structural provinces and their terrestrial continuations

through New Zealand show the present distribution of dominance of the particular trends.

The dominance in the Northwestern and Chatham Provinces can well have persisted from at least early Tertiary times. From late-Tertiary time to the present the Kermadec trend has been the only obviously active crustal deforming process.

The expression of the Northwestern and Chatham trends, due to the nature of the evidence, can be seen as broad folds. Though the Kermadec trend is principally obvious ashore from major NNE-oriented faults, with strong horizontal components, yet to the north of New Zealand the bathymetric evidence does no more than reveal a similar pattern of highs and deeps as in the other provinces.

The variation in geographic position with geologic time of similar structural province boundaries could account for the variability of trend exhibited by pre-Tertiary folds in New Zealand.

References

Brodie, J. W., 1952: Features of the sea-floor west of New Zealand. N.Z.J. Sci. Tech., B, **33** (5), 373—384. — Eiby, G. A., 1955: The seismicity of Auckland City and Northland. N.Z.J. Sci. Tech., B, **36** (5), 488—494. — Fleming, C. A., 1951: Some post-Miocene changes in New Zealand environments. N.Z. Sci. Rev. **9** (10), 166—171. — Fleming, C. A., 1952: The White Island Trench: A submarine graben in the Bay of Plenty. Proc. 7th Pac. Sci. Congr. **3**, 210—213. — Fleming, C. A., and Reed, J. J., 1951: Mernoo Bank, east of Canterbury, New Zealand. N.Z.J. Sci. Tech., B, **32** (6), 17—30. — Hayes, R. C., 1941: Earthquake origins in the New Zealand region. N.Z.J. Sci. Tech., B, **22** (5 B), 225 B—230 B. — Hayes, R. C., 1953: Some aspects of earthquake activity in the New Zealand region. Proc. 7th Pac. Sci. Congr. **2**, 629—636. — Lillie, A. R., 1951: Notes on the geological structure of New Zealand. Trans. Roy. Soc. N.Z. **79** (2), 218—259. — Macpherson, E. O., 1946: An outline of late Cretaceous and Tertiary diastrophism in New Zealand. N.Z. Dept. Sci. Ind. Res. Geol. Mem. **6**. — Raitt, R. W., Fisher, R. L., and Mason, R. G., 1955: Tonga Trench, in Geol. Soc. Amer. Spec. Paper **62**, 237—254. — Wellman, H. W., 1954: Stress pattern controlling lode formation and faulting at Waihi Mine and notes on the stress pattern in the northwestern part of the North Island of New Zealand. N.Z.J. Sci. Tech., B. **36** (3), 201—206. — Wellman, H. W., 1957: Structural outline of New Zealand. N.Z. Dept. Sci. Ind. Res. Bull., **121**.

OOLITIC IRON FORMATIONS IN NORTHERN AUSTRALIA[1])

by A. B. EDWARDS[2])

With 1 Figure and 22 photographs ("Plates")

Summary

Recent exploration in northern Australia has discovered three shallow water oolitic iron formations, one of Permian age, and two of Upper Proterozoic age. The Permian formation resembles the oxidized oolitic chamositic formations of south-eastern England, but contains more detrital quartz and felspar.

The two Precambrian iron formations, consist, below the zone of weathering, of oolites of hematite and of a chamosite-like substance, in a siderite cement, together with well-rounded quartz grains, and are interlayered with sandstones with a chamosite-like cement. Within the zone of weathering the siderite and chamosite are more or less completely replaced by quartz, but with preservation in detail of original textures.

Introduction

Until recently the known iron formations in Australia comprised —

(1) numerous, but individually small, bodies of magnetite, of contact metamorphic or hydrothermal origin, mostly of Palaeozoic age, and concentrated in eastern Australia and Tasmania; and,

(2) larger deposits of hematite, of Precambrian age, associated with much more extensive low grade banded iron formations (variously equivalent to itabirite, jaspilite, taconite or banded hematite-quartzites), generally regarded as metamorphosed sediments. Of the two major formations of this type, that in the Middleback Range of South Australia appears to consist of metamorphosed chemically precipitated sediments (EDWARDS, 1936, 1953; MILES, 1954), while that at Yampi Sound, in Western Australia, consists of clastic sediments resulting from the erosion and re-deposition of former chemically precipitated sediments (CANAVAN and EDWARDS, 1938; REID, 1958).

Recent exploration in northern Australia has brought to light three occurrences of oolitic iron formations, one of Permian age, in the Desert Basin of north-western Western Australia, and two thought to be of Precambrian (Upper Proterozoic) age, one in the Roper River area of the Northern Territory, and the other in the Constance Range area (north-west of Lawn Hills) in north-western Queensland. The two Precambrian occurrences are of considerable extent.

Oolitic ironstones in the Desert Basin, W.A.

The Desert Basin is an extensive area of sedimentary rocks centred on the Fitzroy River, and extending for more than 200 miles south-east from Derby, in north-western Western Australia. The oolitic iron formation was

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discovered in 1952, by A. W. Lindner, then geologist to the Bureau of Mineral Resources, and the nature of the occurrence was confirmed by a petrological examination of a suite of specimens by officers of the Mineragraphic Investigations Section of C.S.I.R.O. (Mineragraphic Report No. 540, June, 1953). The general geology of the region has been described by Guppy, Lindner et alia (1952).

The oolitic iron formation lies in the basal portion of the Liveringa Group, which is the uppermost Permian formation in the region. The Permian sediments are more or less confined to an 80 mile wide section known as the Fitzroy Basin, between the Fenton Fault on the south-west and the Devonian limestones of the Napier and Oscar Ranges on the north-east,

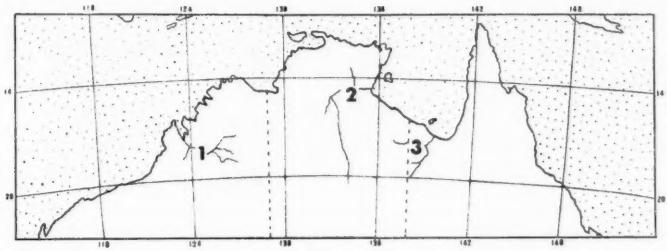

Fig. 1. Location of Oolitic Ironstone Formations in Northern Australia: 1. Desert Basin Ironstones, 2. Roper Bar Ironstones, 3. Constance Range Ironstones.

and centred about Lat. 18° 30′ S., Long. 125° E. (Fig. 1). They have been folded into gentle anticlines and synclines that strike about ESE, and reversals of pitch cause them to outcrop as elongated domes and basins.

The Liveringa Group is a marine formation, about 1200 ft. thick, consisting of ferruginous and calcareous sandstones and shales. The oolitic iron formation occurs as lens-like bodies in a ferruginous sandstone, about 60 to 80 ft. thick, which forms the basal unit of the Group, and outcrops as low strike ridges. The lenses lie along a profusely fossiliferous horizon that persists over a considerable area, and serves as a marker horizon, but are themselves of limited extent.

Near Mount Wynne, and also south of the Grant Range, the oolitic lenses are only a few feet thick, and less than 200 yards long. A much bigger body occurs north of the Grant Range. Here the Lower Liveringa beds form a ridge up to 100 ft. high that extends for about 17 miles from the Fitzroy River in the west, near the old Lower Liveringa Homestead, to the Derby-Liveringa road. The ridge has a steep southern slope, and at about a mile from its western end there outcrops a body of oolitic ironstone from 5 to 30 ft. thick, which extends along the strike for about a quarter of a mile, dipping 5°—8° N. Further smaller lenses, about 1 ft. thick, outcrop intermittently on the southern slope of the ridge for a further 10 miles to the east.

A still more extensive outcrop occurs in the Shore Range, in the south-eastern part of the Basin, where the oolitic iron formation is exposed in an asymmetrical anticline, the limbs of which dip at 5° N, and 20°—25° S.

The specimens examined petrologically came from four localities —

(1) north of Jimberlura Tank, on the north-west flank of the Mount Wynne structure.
(2) from the Lake Liveringa Ridge, on the north flank of the Grant Range Structure.
(3) from the Shore Range, south of the Albert and Surprise bores.
(4) from the Shore Range, south of the Rexona bore.

They consist essentially of limonitic oolites and angular grains of quartz and felspar, together with limonite casts of gasteropods and pelecypods, cemented by limonite; and bear a considerable resemblance to the oxidized oolitic iron formations of Jurassic age mined in the Kettering-Corby district of England.

The limonitic oolites are yellowish-brown to brown, and are distinctly zoned, pleochroic and anisotropic (Plate 1). A proportion of them have fibrous cores, in which the fibres lie parallel and show straight extinction. They resemble somewhat the expanded flakes of altered biotite associated with many glauconite deposits. Occasionally the fibres are spread fan-wise. Very occasional oolites have a core of fossil shell, replaced by limonite, or of mineral grains. The variation in colour in the different specimens suggests variable water content in the limonitic substance. These features parallel those shown by the limonitic oolites in the English ironstones, leaving little doubt that the limonitic oolites have resulted from the oxidation of oolites of chamosite or a closely related mineral. The oolites in the West Australian specimens are deeper brown and less translucent than the oolites in the oxidized English formations. This, combined with the replacement of the fossil shells by limonite, points to a more intense oxidation of the Western Australian rocks, and a greater dehydration of the limonite in them, compared with the English specimens, in which the shell fragments are still calcareous.

A further point of difference is that the Desert Basin rocks contain a significant proportion of quartz and fresh felspar (both microcline and oligoclase), in angular to subangular grains about 0.25 mm. to 0.5 mm. across, together with a small proportion of muscovite and some fragments of quartzite. The amount of quartz and felspar varies from section to section, ranging from 10 to 30 per cent of the rock.

Chemical analyses of several of the Desert Basin oolitic formations are shown in Table 1, where they may be compared with an analysis of oxidized oolitic ironstone from the Preston's Field Pit, England. The significant differences are in the high and variable silica contents, and the high alumina contents of the Desert Basin specimens, and the absence from them of carbonate. The phosphorus content is distinctly higher in some of the analyses, but the manganese contents are similar.

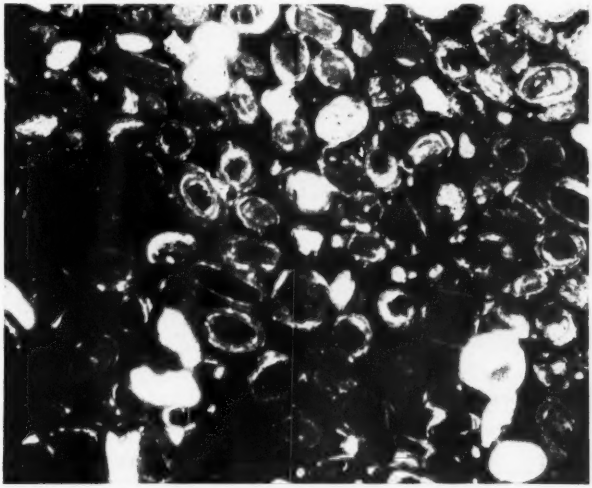

Plate 1. Oolitic ironstone from the Desert Basin, W.A. The concentrically banded oolites consist of translucent limonite in various colours of yellow and brown. The cement is opaque limonite. The white areas are partly quartz, partly plucked out oolites. Ordinary transmitted light, × 25.

Plate 2. Pisolitic ironstone from Roper Bar, N.T., showing portions of three finely banded pisolites (2 to 3 mm. in diameter) of hematite, and their matrix of quartz grains (light grey) cemented by crystalline hematite (white). Black areas are pits. Reflected light, × 25.

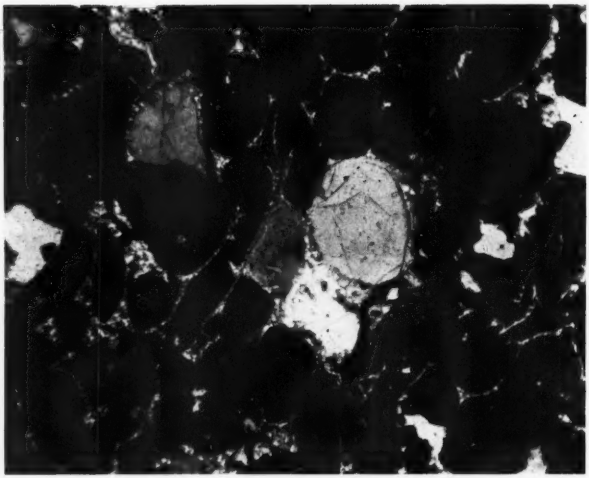

Plate 3. Oolitic ironstone from Roper Bar, N.T., showing oolites of ochreous red hematite (black), and rounded grains of quartz (grey and white), outlined by films of microcrystalline quartz cement (speckled). The proportion of microcrystalline quartz cement marks about the limit between Type A ironstone (less cement) and Type B ironstone (more cement). Transmitted light, crossed nicols, × 35.

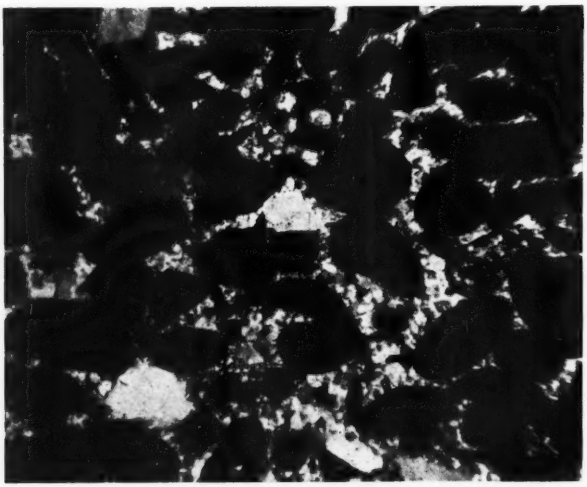

Plate 4. Oolitic ironstone from Roper Bar, N.T., showing rolled and deformed hematite oolites (black), and an occasional quartz grain (white) set in microcrystalline quartz cement (speckled). The proportion of microcrystalline cement marks about the limit between Type B ironstone (less cement) and Type C ironstone (more cement). Transmitted light, crossed nicols, × 35.

Table 1. Chemical Composition of Oolitic Iron Formations in the Desert Basin

	1.	2.	3.	4.	5.	A
SiO_2	19.10	24.00	34.65	28.28	30.79	7.68
Al_2O_3	12.81	11.29	10.13	12.76	10.73	6.34
Fe_2O_3	50.63	48.44	38.0	42.91	43.10	60.16
MgO	0.30	—	—	0.38	0.35	0.32
CaO	0.16	—	—	0.12	0,18	7.14
H_2O+	11.73	—	—	9.98	9.45	8.72
H_2O-	1.97	—	—	3.05	2.77	4.45
CO_2	tr.	tr.	tr.	tr.	tr.	4.53
TiO_2	0.15	—	—	0.04	0.05	0.02
P_2O_5	0.41	1.71	1.85	0.33	0.32	0.28
MnO	0.50	0.53	0.41	0.48	0.46	0.51
Fe	35.4	33.9	26.6	30.0	30.1	42.1
P	0.18	0.75	0.80	0.14	0.14	0.12

1. North of Jimberlura Tank, NW. flank of Mount Wynne structure.
2. Audrey Ridge, SE. of Mount Wynne Creek.
3. Lake Liveringa Ridge, bulk sample of 30 ft. thick lens, north of Grant Range.
4. Shore Range, south of Albert and Surprise bores.
5. Shore Range, south of Rexona bore.

A. Oxidized ore, Preston's Field Pit, Corby district, England.

Oolitic iron formation at Roper Bar, N.T.

During 1954—55 a much more extensive oolitic ironstone formation, extending south-westwards from Roper Bar (approx. Lat. 15° S., Long. 134° E.), the tidal limit of the Roper River, in the Arnhem Land portion of the Northern Territory (Fig. 1), was discovered by G. W. COCHRANE, then geologist to the Broken Hill Proprietary Company Limited.

The formation consists of up to three flat-lying to gently folded beds of cross-bedded ironstone, separated by beds of sandstone and shale, with the following ranges in thickness. —

	Thickness (ft.)
1. Shale and sandstone overburden	up to 40
2. Upper Ironstone bed	3—12
3. Sandstone, with some shale	5—15
4. Middle Ironstone bed	12—40
5. Shales and thin sandstones	30—70
6. Lower Ironstone bed	3—30
7. Shales, in part ferruginous	?

The ironstones occur in two basins (COCHRANE and EDWARDS, 1959). The larger, which is more or less rectangular with its long axis trending NE—SW, is about 1200 square miles in area. Mount McMinn, an isolated mesa near Roper Bar, is its most north-easterly outcrop. The smaller basin

occupies about 300 square miles to the south-east of the old St. Vidgeon homestead. Over much of these areas the ironstones have a low iron content, but a number of areas within the larger basin are of sufficiently high grade to warrant examination.

In the course of the exploration and testing of these areas, suites of specimens representing sections of natural cliff exposures, and of test shafts, together with a series of bulk samples, were submitted to C.S.I.R.O. Mineragraphic Investigations for examination (C.S.I.R.O. Mineragraphic Reports Nos. 640, 662, 663, 670, 694, 695).

The ironstone beds are pronouncedly oolitic. The oolites consist of narrow concentric shells of soft ochreous red hematite, with occasional shells of hard crystalline blue-black hematite, and range in size from 0.2 mm. diameter to about 8.0 mm. diameter, when they are perhaps best described as pisolites. In any one specimen they tend to be more or less uniform in size; and they consist of 50 or more concentric shells, some with a nucleus of a rounded grain of quartz, and less commonly with a nucleus of crystalline blue-black hematite. The ochreous hematite is difficult to polish, but the general form of the oolites, their spacing and their matrix can be seen from Plate 2. The identification of the ochreous mineral of the oolites as hematite was confirmed by an x-ray powder photograph.

In the coarsest specimen observed the pisolites are 7 to 8 mm. diameter, and just touch each other, or are isolated in a matrix of sand-size quartz grains cemented by crystalline blue hematite. The quartz grains are 0.05 to 0.5 mm. across, and are mostly well rounded. The cementing hematite fills the interstices between the quartz grains, and in places forms rims around the pisolites. It also forms occasional veinlets, up to 1 mm. wide, cutting through the quartz-hematite matrix, and penetrating cracks in some of the pisolites, where it may penetrate between shells of ochreous hematite, forming one or more thin concentric shells of crystalline hematite. In places it has penetrated to the core or nucleus of the pisolite. Some of the rims consist of minute bladed crystals of hematite. In the matrix it occasionally forms networks of minute bladed crystals, and occasional massive patches up to 1 mm. across.

The pisolites readily break free from the matrix, and can be separated from it with the fingers. Small samples of the pisolites and the matrix, separated in this way, were analysed for their silica content. The pisolites yielded 7 per cent SiO_2, and the matrix 32 per cent SiO_2. The pisolites constitute about 50 per cent by volume of this specimen.

In a similar specimen in which the pisolites are 3 to 5 mm. diameter, they commonly contain nuclei consisting of single well rounded grains of quartz about 1 mm. across. In places the pisolites are in contact with each other, when they are commonly flattened at the contact, or otherwise distorted (Plates 4, 6), indicating that the rock was compacted while the pisolites were still plastic. Some of the pisolites show internal distortions, as if their central portions were sheared or flattened before the outer shells of ochreous hematite were deposited. A few have double nuclei.

Plate 2 shows a polished surface of this specimen. In places such iron-

stone occurs in beds up to 12 ft. thick, and assays 51.5 per cent Fe and 20 per cent SiO_2. Beds of similar thickness, but consisting of smaller oolites (0.5 to 1.0 mm. diameter) assay 47.5—53.5 per cent Fe and 27.0—19.5 per cent SiO_2. The overall volume of such coarsely oolitic beds is, however, small. In general the oolites are less than 1.0 mm. across.

Examination of individual hand specimens of the ironstones under a binocular ore microscope at magnifications of 18 and 36 diameters, permits their grouping into four main types, which are designated Types A, B, C and D.

Type A appears under the binocular microscope as massive closely packed oolites of ochreous red hematite, with varying, but minor amounts of well rounded quartz grains, about the same size as the oolites, but with no or very little siliceous cement. In a number of such specimens the ochreous oolites have an outermost skin of crystalline blue-black hematite, and in these specimens rounded grains of massive fine-grained hematite and occasional rounded, but elongated flat "pebbles" up to 2 cm. long of similar hematite were present. A proportion of the Type A specimens shows some degree of conversion of the ochreous hematite to brown limonite, and in these specimens the limonite forms a cement between the oolites.

Type B specimens are generally similar, but in them there is a distinct amount of siliceous cement, filling the interstices between the closely packed oolites, quartz grains and hematite grains.

In Type C the proportion of siliceous cement has increased so that it constitutes upwards of half the specimen, and the ochreous red oolites, quartz grains and hematite grains occur isolated in the abundant siliceous cement.

Type D specimens differ from Type C specimens in that the ochreous red hematite oolites have been largely or completely leached away, leaving what is essentially a skeleton of siliceous cement with cavities from which the hematite oolites have been almost wholly leached.

The four types grade into one another.

Thin Sections

The ironstones are difficult to section because of the softness of the ochreous hematite, but if impregnated with a Canada balsam-xylol solution under vacuum, thin sections can be prepared. Microscopic examination of such sections confirms the classification of the hand specimens.

The specimens comprising Type A consist of well rounded quartz grains, with or without silica overgrowths, generally subordinate to banded oolites of ochreous hematite, and some rounded grains of massive crystalline hematite. The oolites and the rounded grains of quartz and crystalline hematite are generally similar in size, and the rock as a whole is well sorted, individual grains being about 0.2 to 0.5 mm. across. Many of the oolites show no visible inclusions of other minerals, but a small proportion have kernels of rounded quartz grains, and a very occasional oolite has a rounded grain of colourless zircon as its kernel. Most of them consist essentially of ochreous red cryptocrystalline hematite that yields an almost scarlet suspension on grinding. A proportion contains narrow bands of cry-

stalline blue-black hematite. No magnetite was observed, and none of the specimens was at all magnetic. In a small proportion of the Type A specimens, the ochreous hematite has been more or less converted to limonite, and where this is accompanied by a development of limonite cement, the oolitic texture of the ironstone is destroyed in some degree. Many of the Type A specimens are free of any cement, or have limonite as a cement, but a proportion of them have thin films of microcrystalline quartz, up to 0.005 mm. wide, cementing the oolites and grains (Plate 3). This microcrystalline quartz cement cannot be detected with the binocular microscope.

A proportion of these specimens contains well rounded flat "pebbles" or pellets, up to 1.0 and even 2.0 cm. long, of massive hematite, or finely bladed crystalline hematite intergrown with minute grains of quartz.

Occasional rounded quartz grains, similar in size to the associated oolites are present in most specimens (Plate 3), and in some bands in the Type A ironstone they are abnormally abundant, the hematite being reduced largely to a cement between the quartz grains. Ochreous hematite oolites are present, but only as a minor constituent, and the ironstone grades into a ferruginous sandstone. In most specimens the quartz grains are fringed with quartz overgrowths (Plate 3), and in places several adjacent rounded grains have been cemented into a patch of "quartzite." In some bands instead of rounded quartz grains there occur rounded fragments of chert, and some of these show concentric banding.

The specimens of the Type A grade into the specimens of Type B by an increase of the amount of microcrystalline quartz cement, until it forms a significant amount of the specimen (about 10 to 15 per cent). Plates 3, 4 may be taken as typical of the texture of the Type B specimens. The ochreous oolites, and the rounded grains of quartz and hematite tend to touch each other, but are on the verge of being isolated in the microcrystalline quartz cement.

The Type B specimens grade into the Type C specimens by a further increase in the proportion of microcrystalline quartz cement, so that in typical Type C rocks the oolites and rounded grains occur isolated in the cement, which constitutes about 50 per cent of the rock (Plate 5 A, B).

In Type C ironstones the ochreous hematite oolites are commonly somewhat flattened, and in some sections are bent and deformed (Plate 4).

The Type D specimens were originally more or less identical in texture with the Type C rocks, but have been leached of their ochreous hematite oolites, so that the former oolites are now represented only by cavities, leaving a rock which consists of rounded grains of quartz, with some grains of crystalline hematite in a cellular mass of microcrystalline quartz cement. The resultant rock is 80 to 95 per cent silica. Some bands of this nature have been logged as sandstone or quartzite in the field (Plates 6, A, B).

Variation within Beds

Comparison of profiles in natural sections and shafts shows lateral variation along the strike of the beds, although the main variation is vertical. The Upper Ironstone bed, where tested, consists of 30 to 60 in. of relatively

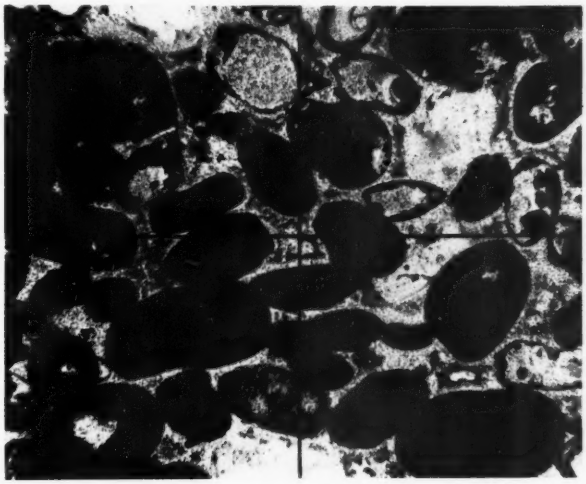

Plate 5 A

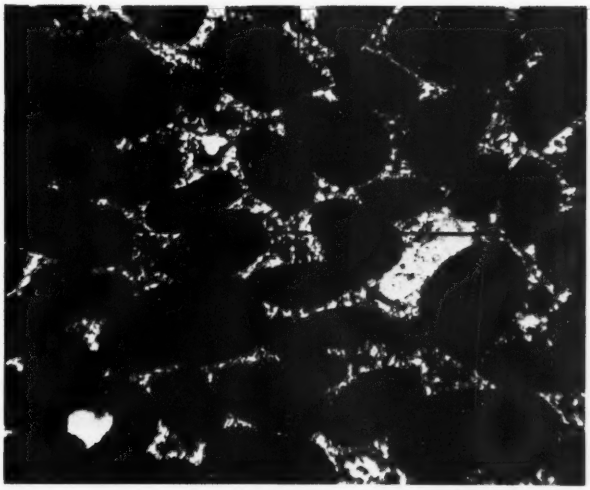

Plate 5 B

Plate 5. A — Ordinary transmitted light. B — Crossed nicols. Type C oolitic ironstone from Roper Bar, N.T., showing ochreous hematite oolites (black), a proportion of which has been leached, leaving cavities rimmed with a little hematite, and occasional quartz grains, in microcrystalline quartz cement. × 35.

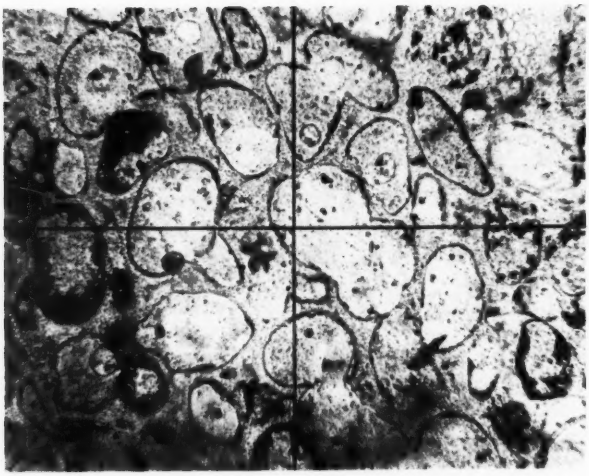

Plate 6 A

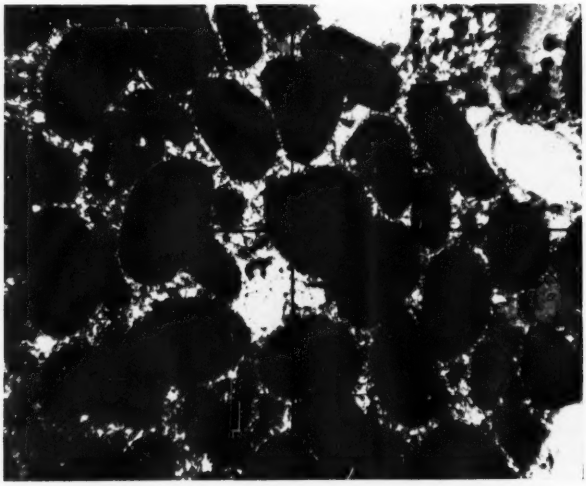

Plate 6 B

Plate 6. A — Ordinary transmitted light. B — Crossed nicols. Type D ironstone from Roper Bar, N.T., originally an oolitic ironstone similar to that shown in Plate 5, but with the hematite oolites more or less completely leached, leaving a skeleton of microcrystalline quartz enclosing the cavities left by leaching out of the oolites. Viewed under crossed nicols the cavities left by the oolites appear black, and the quartz grains white, so that the texture of the ironstone before leaching is apparent. × 35.

good grade ironstone (Type A or B) overlying a variable thickness of severely leached rock (Type D). In places an increase in the proportion of siliceous cement in the upper part of the bed converts it to Type C ironstone.

Similarly the Lower Ironstone bed, where tested, consists predominantly of Type A in its upper part, through thicknesses of 90 to 200 in. below which there is generally an increase in the proportion of siliceous cement.

The Middle Ironstone bed varies more markedly. In places it contains a thickness of up to 200 in. of Type A, elsewhere it consists of Type C and Type D throughout.

Analyses of bulk samples of the Roper Bar ironstones are as shown in Table 2.

Table 2. Chemical Analyses of Bulk Sample of Oolitic Ironstone from Roper Bar area

SiO_2	29.60	10.18	18.52	31.64	23.90
Al_2O_3	2.27	2.55	2.26	1.10	2.39
Fe_2O_3	63.38	82.44	75.89	64.76	68.15
TiO_2	—	—	—	—	tr.
Fe	44.33	57.71	53.12	45.33	47.72
Mn	0.52	0.50	0.13	0.07	0.24
P	0.013	0.015	0.046	0.025	0.044
Ignition Loss	3.30	4.05	2.61	0.86	4.21

Oolitic iron formation at Constance Range, Northwestern Queensland

During 1955—56, geologists of the Broken Hill Proprietary Company Limited discovered a second, and larger, area of oolitic ironstone formation in the Constance Range area, in the extreme north-west of Queensland, about 350 miles south-east of the Roper Bar occurrence (Fig. 1). The Constance Range deposit extends northwards from a few miles west of the former lead-mining township of Lawn Hills (Lat. 18° 38′ S., Long. 138° 40′ E.).

The ironstone occurs in two beds, the upper bed being 10 to 13 ft. thick, and the lower about 30 ft. thick, separated by 8 to 10 ft. of sandstone or quartzite, with some shale. The ironstone contains from 35 to 58 per cent iron, and averages about 53 per cent iron over the areas so far tested. The beds are gently folded, with dips up to 20°, and under a relatively shallow cover of sandstones and quartzites, for many miles form the capping of a number of more or less flat-topped hills. In places they show prominent current bedding, as do the associated sandstones.

A suite of specimens representative of a series of bulk samples from outcrop sections, together with the cores of a series of diamond drill holes, have been examined by C.S.I.R.O. Mineragraphic Investigations (C.S.I.R.O. Mineragraphic Reports Nos. 716, 718, 719).

Red oolitic ironstones

As in the ironstones at Roper Bar, the iron occurs largely as oolites, 0.2 mm. to 1.0 mm. in diameter, consisting of numerous concentric shells

of soft ochreous red hematite, with interleaved shells of crystalline blue-black hematite. The soft hematite is difficult to polish, but the textures of the oolites are revealed in polished sections, despite this (Plates 7, 8, 9), and in thin sections, also, if they are examined in oblique incident light. Some of the oolites enclose cores of rounded quartz grains, others have cores of crystalline blue-black hematite (Plate 9), and a few have cores of quartzite or fine-grained sandstone. Commonly the oolites are flattened into "flax seed" shapes, when they tend to lie with their longer axes parallel to the bedding (Plate 8). Some were more severely deformed while still plastic; others have been broken or sheared, as though brittle. In any one specimen the individual oolites tend to be of uniform size, although the size varies from level to level within the major beds. The common size is 0.5 mm. to 1.0 mm.

The interstices between the oolites are filled with relatively coarsely crystalline quartz that is moulded on them (Plate 10); and the filling of an interstice commonly consists of a single crystal of quartz, or at most about three. In places the quartz crystals are larger, so that the quartz in several adjacent interstices extinguishes simultaneously as a single crystal. The quartz has penetrated shrinkage cracks in the oolites, and spread as thin films between individual concentric shells of hematite (Plate 10). It also fills fractures in the sheared oolites. This quartz, also, is in optical continuity with the quartz filling the interstices.

The quartz tends to be dusty from the presence of innumerable particles of an opaque whitish substance, probably clay, and in many specimens the individual hematite oolites have well defined rims of quartz, which are either clearer than the quartz filling the remainder of the interstice (Plate 11) or darker than it (Plate 12) according to the relative distribution of dust particles. Generally a radial texture is apparent from the lining-up of the dust particles in "strings" which radiate outwards normal to the surface of the oolite. The quartz forming these rims is in optical continuity with the quartz filling the remainder of the interstice; and in places where, say, three crystals of quartz in different orientation fill the interstice, the section of the rim within a particular quartz grain is in optical continuity with that grain, but the rim passes through the three quartz grains without interruption and without disturbance of the pattern of distribution of the dust particles.

In parts of the sections distinct rims are absent, but the strings of dust particles form a radial pattern normal to the surfaces of the oolites, throughout the quartz filling the interstice, and the pattern of the dust particles persists without disturbance through adjacent quartz crystals in different orientation.

These textures (Plates 11, 12) reveal that the quartz cement has replaced an earlier cementing material that had a tendency to concentric and radial textures. None of the original cement remains, but it was probably a carbonate. Moreover, it was introduced into the rock after the oolites had been

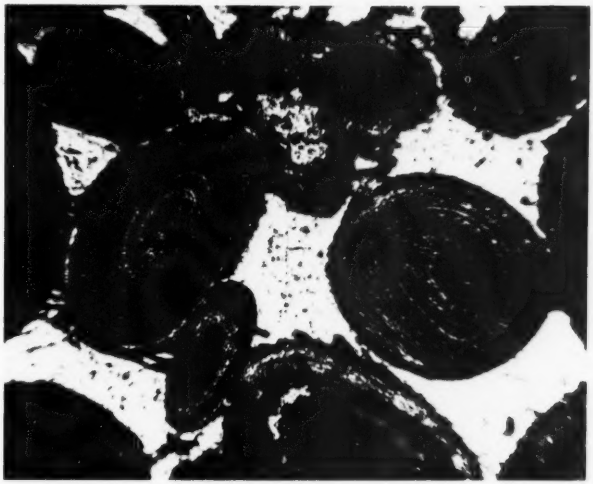

Plate 7. Polished section of red oolitic ironstone from Constance Range, Qld., showing concentric shells of ochreous red hematite (black — not polished) and crystalline hematite (white) in a coarsely crystalline cement of quartz, which appears white against the poorly reflecting ochreous hematite oolites. Reflected light, × 50.

Plate 8. Polished section of red oolitic ironstone from Constance Range, Qld., showing concentric shells in flattened and deformed hematite oolites set in quartz cement, which appears white. The black areas are pits from plucking out of soft ochreous hematite. Reflected light, × 50.

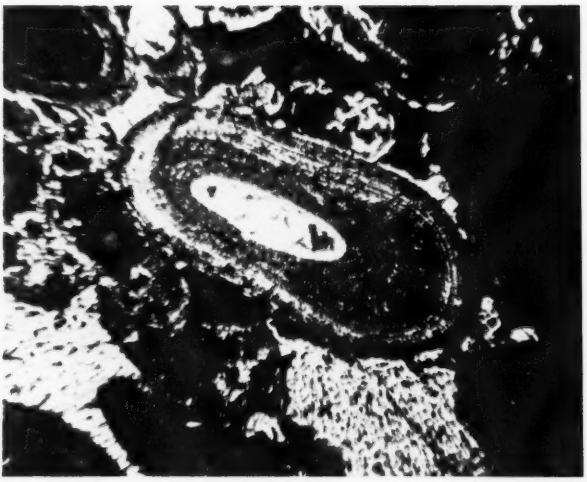

Plate 9. Polished section of red oolitic ironstone from Constance Range, Qld., showing an oolite with a core of dark blue-black crystalline hematite (white) enclosed by shells of ochreous red hematite. The background consists of quartz (speckled white) and cavities (black). (Cf. Plate 20). Reflected light, × 50.

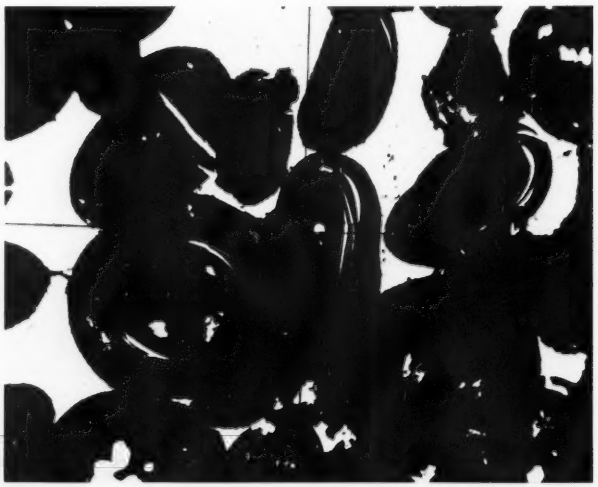

Plate 10. Red oolitic ironstone from Constance Range, Qld., showing hematite oolites (black) in a cement of coarsely crystalline quartz (white). The quartz has penetrated between the concentric shells of the oolites. This quartz is in optical continuity with the quartz in the interstices. Ordinary transmitted light, × 35.

Plate 11. Red oolitic ironstone from Constance Range, Qld., showing oolites of ochreous red hematite (black) in a cement of dusty quartz (white). The distribution of dark particles in the quartz reveals a zonal and radial texture inherited from a previous cementing substance which the quartz has replaced. Ordinary transmitted light, × 50.

Plate 12. As in Plate 11, but with a dusty zone marginal to the oolites, and a clear central area in the interstitial quartz cement. (Cf. Plate 18). Ordinary transmitted light, × 50.

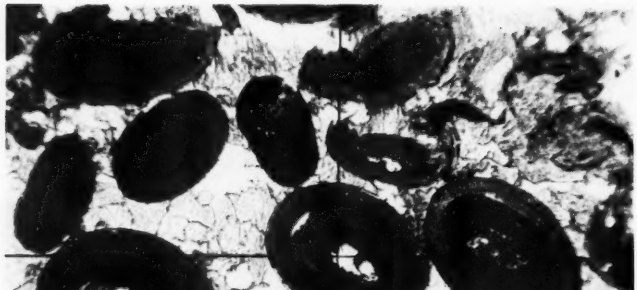

Plate 13. Oolitic siderite from Constance Range, Qld. (DDH. 10 A), showing oolites of a green chamosite-like substance, consisting of pale green or brownish-green outer shells enclosing darker shells containing black opaque carbon and siderite (white) in a cement of crystalline siderite. Some of the oolites near the top of the field of view are deformed. Ordinary transmitted light, × 30.

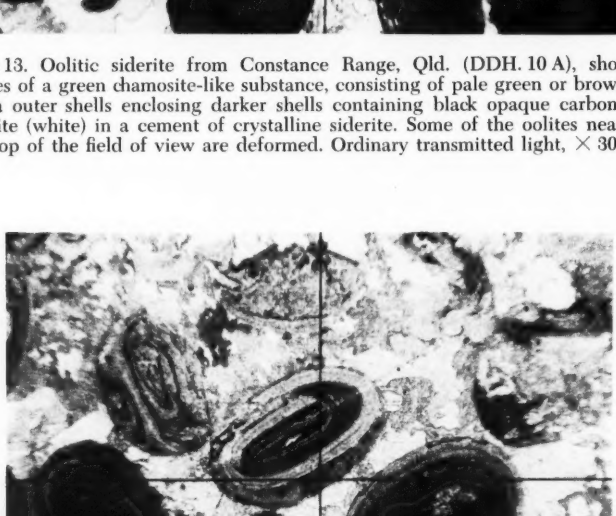

Plate 14. A group of distorted chamositic oolites from the band of rock adjacent to the band of undeformed oolites shown in Plate 13. Ordinary transmitted light, × 30.

deformed, and transported to their present site, as evidenced by their layering parallel to bedding planes when they are flattened.

The red oolitic ironstones generally contain a small proportion of well-rounded quartz grains of detrital origin, similar in size to, or a little larger than, the oolites. The quartz grains have developed overgrowths of later quartz.

In some specimens the hematite oolites are largely replaced by quartz. The replacing quartz shows successive stages of crystal growth, the successive sets of crystal faces being outlined by hematite dust. In some oolites only a thin outer shell of hematite remains. Occasionally the oolites are replaced by opaline silica which preserves the original concentric banding.

A number of specimens contains very occasional well-rounded flat pellets or pebbles, up to 15 mm. × 15 mm. × 3 mm. of banded hematite-bearing rocks. Some of these look like water-worn rock fragments; others show plastic deformation and appear to be flattened oversize oolites (pisolites). The rock fragments resemble angular fragments of ferruginous shale resulting from local contemporaneous erosion, forming micro-"erosion breccias" in one of the drill cores.

In most of the drill core sections, the red oolitic ironstones appear "pocked". This results from a local absence of quartz cement over areas 2 to 3 mm. across, giving rise to the equivalent of small vughs, into which project free surfaces of the adjacent oolites.

Blue hematite ironstone

Locally, in individual sections of the red oolitic ironstones, the quartz cement is replaced by a cement of crystalline blue-black hematite, over areas up to 10 mm. across, giving the rock a dark mottled appearance. With increase in the amount of crystalline hematite cement, the dark colour extends to the rock as a whole. In some specimens the red hematite oolites are still abundant, but commonly the oolites are not apparent, and the rock resembles a dark quartzite.

Thin sections reveal that these rocks contain a number of well rounded quartz grains, generally showing quartz overgrowths, in addition to the cementing quartz. In general, however, the blue-black crystalline hematite has substituted for much of the quartz cement. Oblique incident light reveals in most specimens a number of more or less altered red-brown oolites set in the crystalline hematite cement. They are commonly poorly defined, and show all stages of mergence into the crystalline hematite, being reduced in the final stages to irregular reddish patches.

These rocks contain as much iron as the red oolitic ironstones, with which they are interleaved, and constitute a significant volume of the iron formations, particularly the upper bed. In the lower bed they appear chiefly in the basal part.

Ferruginous sandstones

Interleaved with the blue hematite ironstones, and not easily distinguished from them in hand specimen, are thin beds of dark blue-grey

ferruginous sandstone of somewhat variable iron content and grain size. They consist of equigranular grains of quartz, from 0.05 mm. to 0.2 mm. across, with a varying proportion of hematite cement (Plate 21). Many of the quartz grains were originally well rounded, but have developed irregular quartz overgrowths. Some of the sandstones contain a number of well rounded (second cycle) detrital grains of tourmaline, and less numerous grains of zircon and leucoxene. With a decrease in the amount of hematite cement these rocks grade into normal, or slightly ferruginous, quartzites and sandstones, such as separate the two ironstone formations, and occur above and below them. Occasional isolated oolites of hematite, about 0.5 mm. in diameter, are sparsely distributed through them, sufficient to establish a relationship to the oolitic formations.

A proportion of the sandstones contain what may be oolites, or altered oolites, consisting of well rounded cores of quartz with a thin outer shell of red hematite or blue hematite. In some sandstones these "oolites" are a major component.

Oolitic Siderite

The ironstones exposed in outcrops and intersected in shallow drill holes near the southern, eastern and north-eastern margins of the formation, at localities more than 40 miles apart, are consistently similar, but somewhat different rocks were encountered on the equivalent horizon in a deeper hole (DDH. 10 A) more centrally situated. This hole intersected an oolitic siderite formation between 123 ft. and 141 ft. depth. Chips taken at 124 ft., 128 ft., and 133 ft. assayed 60.1 per cent FeO, 52.3 per cent FeO, and 62.3 per cent FeO, respectively, with only traces of CaO and MgO.

The uppermost siderite bed consists of spherical to slightly flattened oolites 0.3 to 0.5 mm. in diameter in a cement of colourless to pale brown equigranular siderite. The original matter of the oolites has been largely replaced by siderite, which has penetrated between the concentric shells, and commonly only the outermost concentric shells of the oolite remain as thin red-brown shells enclosing relatively coarsely crystalline siderite (Plate 18). All stages of the replacement can be observed, and it is accompanied by the development of patches of black amorphous carbon (Plate 17). The carbon, which is much softer than the siderite, polishes readily, and in reflected light resembles graphite in colour, but is isotropic in contrast with the intense anisotropism of graphite. An x-ray powder pattern confirms its amorphous nature. Where the carbon is abundant the rock is grey-black to brownish-black. Commonly these dark siderites consist of closely packed, flattened oolites, largely replaced by siderite and black amorphous carbon (Plate 16).

In a number of thin beds the oolites consist of pale green or brownish green chamosite or a chamosite-like substance, occurring as a number of concentric shells (Plates 13, 14, 15). The chamositic oolites show all stages of replacement by siderite, with the development of patches of carbon (Plates 15, 16); and in places they show stages of

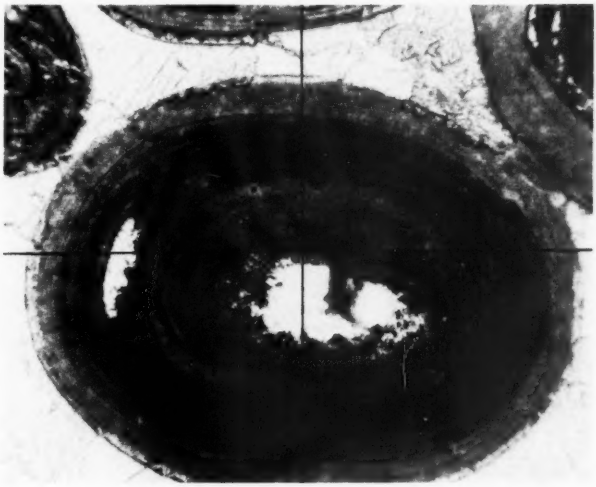

Plate 15. Chamosite-like oolite showing numerous concentric shells in varying colours of pale green and brownish-green. The core of the oolite, and parts of some intermediate shells have been replaced by siderite (white). The "chamosite" adjacent to the siderite tends to be studded with fine particles of carbon. Constance Range, Qld. (DDH. 10 A). Ordinary transmitted light, × 100.

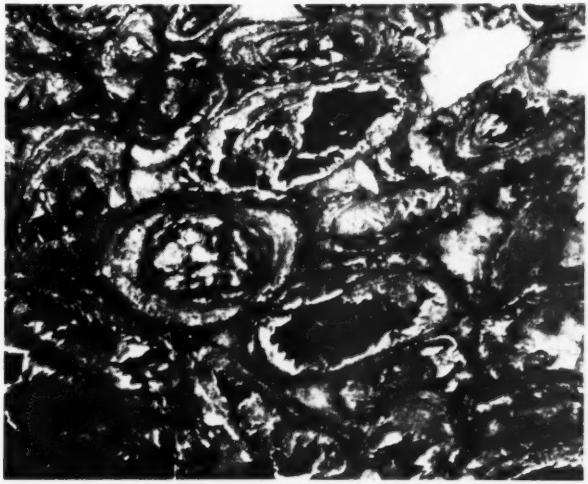

Plate 16. Carbonaceous oolitic siderite from Constance Range, Qld. (DDH. 10 A), in which closely packed oolites are largely replaced by siderite and black amorphous carbon. An occasional area of quartz (white) substitutes for siderite in the cement. Ordinary transmitted light, × 30.

Plate 17. Oolite consisting of a red-brown iron oxide rim and a core of concentric shells partly replaced by clear crystalline siderite (light grey) and some carbon (black). Constance Range, Qld. (DDH. 10 A). Ordinary transmitted light, × 75.

Plate 18. Oolitic siderite, consisting of oolites composed of red-brown iron oxide rims and siderite cores, in siderite cement. The cement shows a crustification texture where it is moulded on the oolites, the zoning being emphasised by radially arranged dust-like inclusions. This marginal zone consists of minute columnar crystals of siderite, whereas the clear siderite filling the rest of the interstice consists of a single coarse crystal. (Cf. Plates 11, 12.) Constance Range, Qld. (DDH. 10 A). Ordinary transmitted light, × 30.

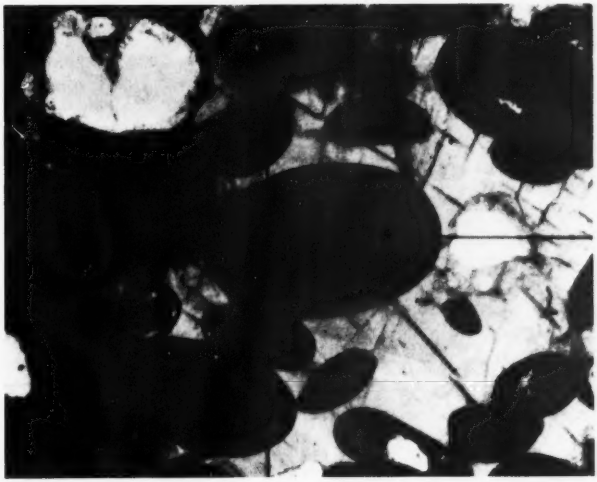

Plate 19. Red oolitic siderite from Constance Range, Qld. (DDH. 2 B) showing oolites of soft ochreous red hematite (black), and grains of quartz (white), one with an overgrowth, set in a cement of coarsely crystalline siderite, showing cleavage traces. Ordinary transmitted light, × 30.

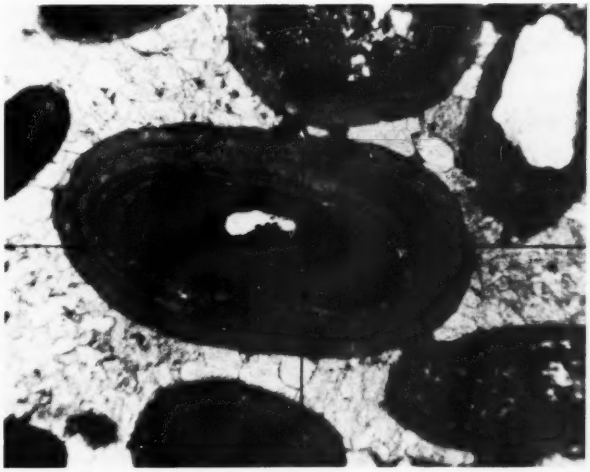

Plate 20. Oolitic siderite from Constance Range, Qld. (DDH. 2 B) showing an oolite consisting of a pale green chamosite-like substance interleaved with hematite (black), and with a central zone of hematite around a nucleus of quartz (white), set in siderite cement. Ordinary transmitted light, × 75.

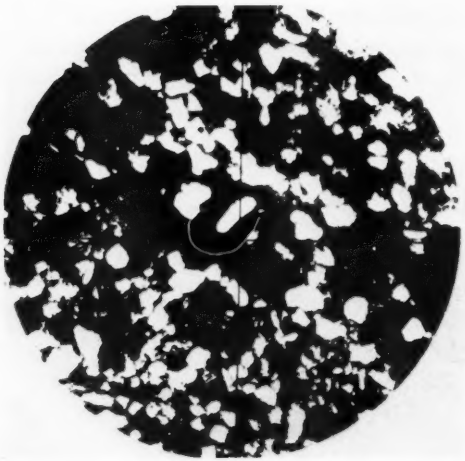

Plate 21. Fine-grained ferruginous sandstone, consisting of quartz grains in a hematite cement (black). Constance Range, Qld. Ordinary transmitted light, × 30.

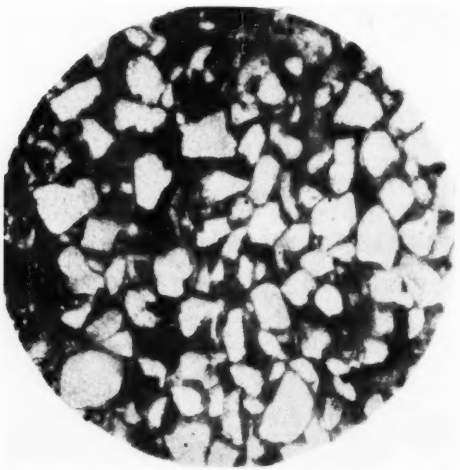

Plate 22. Fine-grained green sandstone, consisting of quartz grains in a cement of pale green chamosite-like substance (grey). The black patches are dark brown siderite. Constance Range, Qld. (DDH. 10 A). This rock is interlayered with the oolitic siderite. Ordinary transmitted light, × 30.

alteration to yellowish and red-brown iron oxide. The impression is gained that all the oolites in the siderite beds were originally composed of this chamosite-like substance prior to the introduction of the siderite cement.

The siderite filling the interstices between the oolites is commonly clear and coarsely granular, when it is possibly recrystallized. In a number of sections it is partly cloudy from the presence of dust-size particles of an opaque whitish substance (? clay). When clouded it commonly shows a narrow concentric band or crustification, around the oolites bounding the interstice, combined with a radial arrangement of the dust particles within this zone (Plate 18). This texture matches the relict textures in the quartz cement of the red oolitic ironstones (Plates 11, 12). The narrow zone encrusting the oolites commonly consists of minute columnar crystals of siderite, with their long axes normal to the surfaces of the oolites, producing an alignment of the dust particles, while the central part of the interstice within this zone is filled with a single coarse crystal of siderite. In some sections the concentric texture is present, but the siderite filling the interstice consists of either a single coarse crystal or several such crystals, which include as part of them the zone moulded on the oolites. Presumably here the siderite has recrystallized, but without disturbing the dust particles. This texture is the exact counterpart, in siderite, of that observed in the quartz cement of the red oolitic ironstones. This texture is found enclosing flattened and distorted oolites as well as spherical oolites, so that the cementation occurred after the deformation of the oolites.

Black siderite and green sandstones

Interlayered with the oolitic siderite, particularly towards the base of the formation, are narrow bands or beds, from 1.0 mm. to 20.0 mm. thick of massive, very fine-grained dark-brown siderite, which appears as black bands, commonly alternating with slightly thicker bands or beds of pale green sandstone. The green sandstone consists of quartz grains in a pale green chloritic or chamositic cement (Plate 22).

Outcrops

Outcrops in a cliff section about a quarter of a mile to the south of DDH. 10 A, on the horizon of this oolitic siderite formation, consist of weathered and somewhat limonitized, but otherwise typical, red oolitic ironstone, blue hematite ironstone, and ferruginous sandstone. The two sections do not match in thickness, and the outcrop section contains a bed or beds of sandstone separating two ironstone beds which cannot be matched in the drill hole section. However, it would appear that the rocks in the outcrop are the weathered equivalents of the oolitic siderites, where they have undergone oxidation and silicification. In view of their matching textures, such as concentric banding of oolites and crustification of cements, the red oolitic ironstones would correspond to siderite beds with chamositic oolites, while the ferruginous sandstones would correspond to the green (chamositic) sandstones. The ferruginous sandstones, moreover, contain thin bands of massive limonite that match the thin bands of black siderite interleaved with the green sandstones.

A difficulty attending the general application of this interpretation is that the grade of the ironstones at Constance Range is such that most of the iron in the oolitic siderite must have been concentrated into the oolites while the siderite cement was being replaced by quartz. The two changes must have been concurrent to preserve the crustification textures in the quartz cement, and there can have been no change in volume of the oolites during their conversion to hematite. Moreover, the preservation of concentric banding in the ochreous hematite oolites is much more perfect than that shown by most of the oolites so far observed in the oolitic siderite. Most of the oolites must have escaped any previous replacement by siderite.

Red oolitic siderite

These difficulties disappear if the oolites of ochreous red hematite are pictured as primary oolites, originally set in a siderite cement, and the chamositic oolites are regarded as local variants of deposition.

Such a rock has been found in the lower ironstone beds in a second deep drill hole, DDH. 2-B [3]), sunk in the southern part of the area, about a quarter of a mile north of the outcrops and shallow drill holes put down earlier. The rock, which constitutes the greater part of a 35 ft. thick sideritic formation, consists of closely packed red ochreous hematite oolites, showing prominent concentric banding, and an occasional rounded detrital grain of quartz, set in a coarsely crystalline cement of siderite (Plate 19). In places the siderite cement shows encrusting textures around the oolites similar to those illustrated in Plates 11, 12, 18.

Interleaved with these beds packed with hematite oolites are occasional thin beds containing chamositic oolites, also in siderite cement, and others in which the original mineral of the oolites is more or less completely replaced by siderite, or more rarely by quartz. In some beds the chamositic oolites consist of concentric shells of chamositic substance interleaved with occasional shells of hematite, and a number have a hematite core with a quartz nucleus (Plate 20).

It appears certain, therefore, that the ochreous red hematite oolites are not a recent weathering product, but were formed during deposition of the rocks; and that it is only replacement of the siderite cement by quartz that can be attributed to present day weathering processes; and even some of the quartz cement may be of earlier origin. Some of the hematite cement in the blue hematite ironstones and in the ferruginous sandstones may be attributed to weathering processes also, because the beds in DDH. 2-B equivalent to the upper ironstone formation, in which beds of these rock types preponderate, consist largely of quartz grains set in coarsely crystalline siderite. They have a texture comparable with a "Fontainebleau sandstone", and may be described variously as sandy siderite or sideritic sandstone, according to the proportion of quartz present. Thin beds of oolitic siderite and green sandstone are interleaved with them.

[3]) Also in subsequent deep drill holes.

Conversion of the siderite to hematite would yield typical blue hematite ironstones and ferruginous sandstones. Some blue hematite ironstones, however, are of earlier origin, because occasional bands of such rock are interleaved with the red oolitic siderite in the lower iron formation.

The two sideritic formations in DDH. 2-B are separated by 8 ft. of thinly bedded and rapidly alternating black slates and green sandstones (quartz in a chamosite-like cement, Plate 22) showing current bedding combined with textures indicating contemporaneous erosion of the black slates ("slump" structures).

Conclusions

These oolitic ironstones are new lithological types for Australia. The Permian oolitic ironstones of the Desert Basin are clearly the oxidized outcrops of a chamosite ironstone (or equivalent rock) laid down under shallow water marine conditions. They differ from the oxidized chamosite ironstones in south-eastern England only in a relatively greater content of detrital quartz and felspar.

The two Precambrian ironstones were also laid down under shallow water conditions; but in their outcrops and where under only shallow overburden, they differ from most known oolitic ironstones in their abundant quartz cement, and lack of carbonate minerals. This will necessitate beneficiation if the ironstones amenable to open cut mining are to become sources of iron.

The quartz cement in these rocks is not a primary feature at Constance Range — and by analogy, not at Roper Bar either [4]). The Constance Range rocks originally consisted of oolites of hematite, and of a chamositic substance, with a siderite cement. This composition is preserved where the rocks lie beneath the zone of weathering and the unaltered rocks so far discovered bear a general, though not detailed, resemblance to the oolitic ironstones of Wabana, Newfoundland (Hayes, 1915, 1929). They lack, of course, fossils. Within the zone of weathering, however, silicification has occurred, leading to a replacement of the siderite cement by quartz — coarsely crystalline quartz at Constance Range, and microcrystalline quartz at Roper Bar.

The uniform completeness of the replacement over such wide areas is most striking, but both ironstones are in regions where weathering has been severe and prolonged.

References

Canavan, F., and Edwards, A. B., 1938: The Iron Ores of Yampi Sound, Western Australia. Proc. Aus. Inst. Min. Met., No. 110, 59—101. — Cochrane, G. W., and Edwards, A. B., 1959: The Roper River Oolitic Iron Formations. Proc. Aus. Inst. Min. Met. (in press). — Edwards, A. B., 1936: The Iron Ores of the Middleback Ranges, South Australia. Proc. Aus. Inst. Min. Met. No. 102, 155—207. – 1953: Mineralogy of the Middleback Iron Ores, in Geology of Australian Ore De-

[4]) A recent drill hole at Roper Bar has intersected red oolitic siderite below the zone of weathering.

posits. Proc. Fifth Empire Min. Met. Congr., Melbourne, Vol. I, pp. 464—472. — Guppy, D. J., Lindner, A. W., Rattigan, J. H., and Casey, J. N., 1952: Sediments of the Desert Basin, Western Australia, in Symposium de la Séries de Gondwana, XIXth. Inter. Geol. Congr., Algiers, pp. 107—114. — Hayes, A. O., 1915: Wabana iron ores of Newfoundland. Geol. Surv. Canada, Mem. 78. – 1929: Further studies of the origin of the Wabana Iron Ores of Newfoundland. Econ. Geol., **24**, 687—690. — Miles, K. R., 1954: The Geology and Iron Ore Resources of the Middleback Range Area. Bull. Geol. Surv. South Australia, No. 33. — Reid, I. R., 1958: The Geology of Cockatoo Island, Yampi Sound, Western Australia. Proc. Aus. Inst. Min. Met. (in press No. 188).

ZUSAMMENFASSUNGEN

Die charnockitischen Gesteine Australiens. A. F. Wilson.

Die Struktur der Umgebung der sieben bekannten Charnockit-Gebiete Australiens und die in diesen auftretenden Hauptgesteinstypen werden beschrieben. Die Darstellung wird gestützt von repräsentativen chemischen Analysen, von denen eine Reihe neu sind. In einigen Gebieten herrschen Gesteine in metamorpher Granulitfazies vor, in anderen stecken die Charnockite als Relikte in Gesteinen der Amphibolitfazies. Die Nähe der meisten Gebiete zu großen Störungszonen legt die Vermutung nahe, daß die wohlbekannte, den meisten Charnockiten eigene Textur entweder durch Wärmeleitung längs tiefgelegener Überschiebungen und Scherzonen oder durch Herabsinken von Grundgebirgsteilen in wärmere Zonen an Verwerfungen entstanden ist.

Die meisten zur Verwandtschaft der Charnockite gehörenden Gesteine Australiens sind durch Metamorphose entstanden. Die basischen Gesteine sind meistens metamagmatisch, viele von ihnen sind durch die Metamorphose beträchtlich verändert worden. Die intermediären sind z. T. metamagmatisch, zum größten Teil jedoch metasedimentär, oder es sind granitisierte basische Granulite. Viele der jetzt als Charnockite vorliegenden Gesteine wurden von mehr als einer Metamorphose erfaßt. Nicht metamorphe saure Orthopyroxen-Gesteine bilden bedeutende Intrusionen in den charnockitischen Komplexen Zentralaustraliens. Diese „Magmen" sind wahrscheinlich durch palingenetisches Aufschmelzen von metamorphen Gesteinen in einer sauerstofffreien Umgebung entstanden.

Das Präkambrium von Nordwest-Queensland, Australien. E. K. Carter.

Präkambrische Gesteine, die vom wahrscheinlichen Archäikum bis zum Oberen Proterozoikum reichen, treten in NW-Queensland in einem 25 000 Quadratmeilen großen Gebiet zutage. Sie lassen sich in 4 große Gruppen aufteilen, die durch starke Diskordanzen getrennt sind. Über die Geschichte der archäischen Gesteine ist nur wenig bekannt. Sie umfassen wahrscheinlich umgewandelte saure Laven, Glimmerschiefer, Gneise und Migmatite. Die Schichten des Unteren Proterozoikums sind Teil eines Orogens. Das untere Unter-Proterozoikum ist reich an sauren und basischen Laven. Es ist maximal nicht weniger als 40 000 Fuß mächtig und wurde durch einen E—W-Zusammenschub stark deformiert. Wahrscheinlich wurde es von Graniten intrudiert, ehe die Folge des oberen Unter-Proterozoikums abgelagert wurde. Diese besteht zum größten Teil aus Sedimenten. Sie erreichen im W und NW des aus tiefstem Proterozoikum bestehenden Gebirgskernes die größten Mächtigkeiten, greifen jedoch auch auf das tiefste Proterozoikum über.

Die maximale Mächtigkeit der Sedimente beträgt wenigstens 40 000 Fuß. Die Folge wurde durch ein Wiederaufleben der in E—W-Richtung angreifenden Kräfte deformiert; die Deformation war von Granitintrusionen begleitet. Die Faltung ist stark bis mäßig, im W des Aufschlußgebietes fehlen ihr jedoch wohldefinierte lineare Elemente.

Sedimente und Laven des Oberen Proterozoikums kamen hauptsächlich in W und NW des Gebietes zur Ablagerung. Sie sind geringfügig bis mäßig an W bis NW streichenden Achsen gefaltet.

Das Präkambrium NW-Queensland tritt, wenn man den Camooweal-Dolomit ausnimmt, in einem Gebiet von 25 000 Quadratmeilen zutage. Die systematische Geländearbeit wurde 1950 von gemischten Arbeitsgruppen des Commonwealth Bureau of Mineral Resources und des Geological Survey of Queensland begonnen.

Die Übersichtskartierung des Gebietes war 1954 abgeschlossen. Die Überarbeitung und Detailkartierung von wirtschaftlich interessanten Gebieten sind noch im Gange. Karten im Maßstab von 1 : 253 440 sind in Vorbereitung, und ein Bericht über das Gebiet wird geschrieben (Carter & Brooks, in Vorbereitung.) Der Camooweal-Dolomit, der ins Obere Proterozoikum oder ins Untere Kambrium gehört, ist darin nicht eingeschlossen. Seine stratigraphische und paläogeographische Stellung wird von Noakes (1956) diskutiert.

Die Rekonstruktion der geologischen Entwicklung des Gebietes ist eine Ausdeutung der beobachteten Einzelheiten. Das Tatsachenmaterial ist nicht vollständig genug, um eine abgeschlossene Interpretation der Entwicklung des Gebietes zu ermöglichen, in der alle Gesichtspunkte berücksichtigt sind. Besonders der Vorgang der Granitintrusion wurde noch nicht vollständig enträtselt.

Die ältesten fossilen Faunen in Süd-Australien. M. F. Glaessner.

Eine kritische Übersicht der bekannten Hinweise auf vorkambrische Fossilien von Süd-Australien führt zu dem Ergebnis, daß das Vorkommen von Radiolarien möglich ist, daß aber alle angeblichen Tierreste aus vorkambrischen Schichten irrtümlich als solche gedeutet wurden. Das behauptete Vorkommen von Arthropoden ist unbewiesen.

Die von Sprigg beschriebene Fauna aus dem „Frühkambrischen" Sandstein und Quarzit von Ediacara enthält nicht nur Medusen. Neue Forschungen haben nachgewiesen, daß darin auch Formen vorkommen, die den Typen von *Pteridinium* und *Rangea* aus der Nama-Serie von Südwest-Afrika ähnlich sind. Diese werden jetzt als Verwandte der lebenden *Pennatulacea* aufgefaßt. In den gleichen Schichten kommen auch *Spriggina* (Annelida), möglicherweise *Siphonophora*, und zwei völlig neuartige Invertebraten vor.

Die Schichten mit dieser Fauna werden von einer Schichtfolge mit zweifellos unterkambrischen Fossilien überlagert, von Archaeocyathiden-Kalken bis zur Protolenus-Zone. Da die Fauna von Ediacara, die nur aus unbeschalten Organismen besteht, von allen bekannten kambrischen Faunen grundverschieden ist, kann ihr ein noch vorkambrisches Alter zugeschrieben werden.

Die Musgrave-Gebirgskette in Süd-Australien. R. C. Sprigg & R. B. Wilson.

Die Strukturelemente, die den östlichsten Ausläufern des westaustralischen Schildes aufgeprägt wurden, haben vorherrschend eine E—W-Richtung. Diese Anlage hat die späteren Orogenesen und die geomorphologische Entwicklung durch die lange Geschichte des Gebietes hindurch ständig beeinflußt und gelenkt. Wahrscheinlich sind zwei Hauptantiklinalzonen in dieser E—W-Richtung

ausgebildet; sie sind bis heute als Bergketten und Inselberge erhalten geblieben. Große batholitische Intrusionen kennzeichnen die südlichere Zone, während die in der nördlicheren Zone ausstreichenden Gesteine vorwiegend metasedimentär sind. Die Granitzone weist eine starke negative Bouguer-Anomalie (— 150 Milligal) auf, die einen großen Dichtenunterschied zwischen den massigen Graniten mit geringer Dichte und den geschieferten Granitgneisen der nördlichen Kette anzeigt. Die Stärke der Erdkruste muß örtlich außerordentlich groß sein, um eine solche nichtkompensierte Last auszuhalten. Dennoch flankieren tiefe Gräben, in denen Sedimente des Oberen Proterozoikums und des Ordoviziums erhalten sind, beide Ränder der negativen Anomalie.

Ringstrukturen, granitische Gesteine und Krustenbrüche in SE-Australien. E. S. Hills.

Die Struktur und Entwicklung von mehreren devonischen Ringstrukturen und den damit verbundenen granitischen Intrusionen, die das Vorhandensein von in der Tiefe gelegenen Ringbrüchen in SE-Australien aufzeigen, werden diskutiert. Der magmatische Komplex von Marysville enthält im Archeron-Kesseleinbruch fisch- und pflanzenführende Schichten. Er hat einen Durchmesser von 15 Meilen und enthält 6000 Fuß mächtige saure Laven, untergeordnet treten Andesite und Basalte auf. Die meisten Vorkommen gehören zu einer magmatischen Sippe. Das Stammagma ist intermediär; es ist den Hypersthen-Daziten des Gebietes sehr ähnlich. Wahrscheinlich ist es als ein Magmakeil von E her intrudiert worden.

Australien und Gondwanaland. C. Teichert.

Die Fortschritte der geologischen Erforschung Westaustraliens während der letzten 20 Jahre haben zu einer verbesserten Einsicht in die geologische Geschichte und die tektonische Bedeutung der großen Sedimentbecken geführt, die sich am Westrand des australischen Kontinents befinden. Vier große Becken sind bekannt, die gegenwärtig (von Norden nach Süden fortschreitend) wie folgt benannt sind: 1. Bonaparte Gulf Basin, mit einem älteren südlichen Anhang, dem Ord Basin, 15 000 qkm; 2. Canning Basin 446 000 qkm; 3. Carnarvon Basin, 116 000 qkm; 4. Perth Basin, etwa 20 000 qkm. Ein 5. Becken, das Eucla Basin an der Südküste, ist von geringerer geologischer Bedeutung. Die 4 erstgenannten Becken sind mit paläozoischen, mesozoischen und känozoischen Sedimentgesteinen gefüllt, deren Gesamtmächtigkeit für die einzelnen Becken zwischen 5500 und 12 000 m liegt. Marine Schichten mit reichen Faunen machen in allen Becken den Hauptanteil der Sedimentmassen aus. Im Carnarvon Basin ist die Schichtenfolge sogar fast gänzlich marin. Alle geologischen Formationen vom Kambrium bis zum Tertiär sind vertreten und enthalten Faunen, die teils zu Europa und Asien, teils zu Nordamerika Beziehungen aufweisen. Eine Analyse des Kontinentalschelfs und der angrenzenden Ozeangebiete zeigt, daß sich die Becken als Depressionen über den Schelfrand hinaus verfolgen lassen. Die Anwesenheit der Becken selbst sowie der Charakter ihrer Sedimente und die Zusammensetzung ihrer Faunen zeigen die Existenz eines Meeres im Westen Australiens an, durch welches der australische Kontinent zumindest seit ordovizischer Zeit nach Westen abgegrenzt wurde. Eine fortlaufende Kontinentalität Australiens seit dem Jungpaläozoikum ist außerdem durch die Zusammensetzung der Landfaunen dieses Kontinents angezeigt. Falls es überhaupt je eine Art Gondwanaland irgendwo gegeben haben sollte, hat Australien jedenfalls niemals dazugehört.

Die Geographie des Sakmara. D. Hill.

Das bekannte paläontologische und stratigraphische Tatsachenmaterial wurde als Unterlage für die Konstruktion von Karten benutzt, die zeigen, in welchem Ausmaße die Kontinente im Sakmara (Unterperm) vom Meer bedeckt waren. Für die nördliche Hemisphäre, außer Indien, ist dieses Material zuverlässig genug, um relativ genaue Karten herstellen zu können. Die Größe der Überflutungen weist darauf hin, daß das damalige Klima sich vom heutigen beträchtlich unterschied; aber unzweifelhaft sakmarische Eiszeiten treten nicht auf. In den südlichen Kontinenten und Indien machte die biogeographische Provinz „Gondwana" die Korrelation mit den nördlichen Kontinenten fragwürdig, doch bestehen Gründe für die Annahme, daß die eiszeitlichen Ablagerungen des „Gondwana"-Landes mindestens teilweise sakmarisch sind. Die Karten zeigen, daß die Festlandsfläche des „Gondwana"-Landes nur wenig reduziert war und daß die Haupteiszeiten (außer in Indien) in einem Gürtel zwischen 40° und 20° südlicher Breite auftreten. Da uns Kenntnisse über die Ausbildung des Sakmara in der Antarktis noch fehlen, ist eine Rekonstruktion von Klimazonen, die zur Aufstellung oder Nachprüfung der Hypothesen der Kontinentaldrift und der Polwanderung dienen könnten, heute noch zu gewagt.

Stratigraphie und Mikropaläontologie der Oberen Kreide West-Australiens. D. J. Belford.

Die Verteilung, die Beziehungen und die stratigraphische Bedeutung der Mikrofaunen (hauptsächlich Foraminiferen) in den Ablagerungen der Oberen Kreide Westaustraliens werden diskutiert, außerdem werden Betrachtungen über die Paläogeographie und Paläoökologie angestellt.

Im Cenoman-Turon wurden der Gearle Siltstein, der Alinga Grünsand und vielleicht der Molecap Grünsand abgelagert. Unter den vorgefundenen Foraminiferen sind die planktonischen Formen *Globotruncana (Praeglobotruncana) stephani* subspp. und *G. helvetica* stratigraphisch begrenzt.

Der Gingin Kalk und der untere Teil des Toolonga Calcilutit wurden während des Santons abgesetzt. Diese Schichten enthalten die Krinoidengattungen *Marsupites* und *Uintacrinus*, mehrere Arten von *Globotruncana* und *Neoflabellina*, ferner *Bolivinoides strigillata*. Schichten des Santons sind nach Norden in Aufschlüssen bis in das Gebiet der Warroora Antiklinale bekannt.

Der Toolonga Calcilutit geht hinauf bis ins untere Campan, hier erscheint *Globotrunca arca* in der Fauna. Das Vorkommen von Campan im Perth-Becken ist nicht zu beweisen; ein großer Teil des Poison Hill-Grünsands hat möglicherweise dieses Alter. Nach den Foraminiferen begann die Ablagerung des Korojon Calcarenit im Campan. Wichtige Gattungen sind *Globotruncana arca, Cibicides voltziana* und *Bolivina incrassata*.

Die oberen Schichten des Korojon Calcarenit und des Miria-Mergels haben Maastrichtalter. Der Miria-Mergel enthält die Arten *Globotruncana stuarti, G. citae* und *G. contusa*. Der obere Teil des Poison Hill-Grünsandes ist möglicherweise ins Maastricht einzustufen.

Die Struktur Neuseelands nach seismischen Untersuchungen. G. A. Eiby.

Das Neuseeländische Gebiet ist durch eine 20—25 km dicke Kruste und eine Unterkruste bis zu einer Tiefe von 370 km charakterisiert. Diese Krusten sind voneinander getrennt durch eine Zwischenschicht, die sich bis zu einer Tiefe von ungefähr 100 km erstreckt. Die Kruste wird durch steil einfallende Verwerfungen in Schollen geteilt. Einige Schollen sind seismisch aktiv, andere

sind stabil. Im Osten wird das Gebiet vom Pazifischen und im Westen vom Tasmanischen Becken begrenzt. Diese beiden Regionen besitzen 6 km dicke ozeanische Krusten.

Eine keilförmige Struktur, worin die Tiefherd-Seismizität eingeschlossen ist, durchquert die Unterkruste. Diese wird Sub-Crustal-Rift genannt und ist wahrscheinlich eine Fortsetzung der Seismizität des Kermadec-Grabens. Sie streicht ungefähr südwestlich von der Bay of Plenty zu Farewell Spit; dann wendet sie sich plötzlich nach SSE und endet in der Nähe der Alpen-Verwerfung (Alpine Fault). Verwerfungen mit NO- und EW-Streichlinien sind gegenwärtig aktiv. Die wichtigste NW-Verwerfung verläuft durch die Cook-Straße.

Es ist anzunehmen, daß sich die Hauptverwerfungen durch aufeinanderfolgende Lagerung über dem Sub-Crustal-Rift entwickelt haben können. Stabile Schollen sind nicht so stark zerbrochen worden. Die Krusten-Struktur auf den beiden Seiten ist wahrscheinlich verschieden. Im Westen ist die Kruste ungefähr 5 km dicker, und sie enthält eine Schicht mit P-Geschwindigkeiten über 7 km/sec. Geschwindigkeiten über $6^1/_2$ km/sec sind im Osten nicht beobachtet worden. Wir haben keine Hinweise auf eine Bogenform der Struktur. Alle Krusten- und Unterkrusten-Strukturen sind anscheinend geradlinig.

Die strukturelle Bedeutung der Ausbildung des Meeresgrundes um Neuseeland. J. W. Brodie.

Die ozeanischen Höhen und Tiefen um Neuseeland sind deutlich linear ausgerichtet. Sie lassen sich in drei Gruppen aufteilen, deren Hauptzüge NW—SE, E—W und NNE—SSW streichen. Diese Gruppen werden als Strukturprovinzen betrachtet — als die NW-, Catham- und Kermadec-Provinz —, die sich sowohl dem Alter als auch der Geographie nach unterscheiden. Die Landmasse Neuseelands liegt an der Stelle, wo die drei Strukturzüge zusammentreffen, und es wird angenommen, daß ihr Relief durch diese Vereinigung bedingt ist.

Anzeichen einer jungen Aktivität an Strukturen, die zur NW- und Chatham-Provinz gehören, sind in Neuseeland nicht beobachtet worden. Das submarine Relief ist wahrscheinlich prätertiären Alters.

An der Struktur der Kermadec-Provinz haben bis in die Gegenwart Bewegungen stattgefunden. Die untermeerische Ausbildung dieses Gebiets ist beträchtlich jünger.

Eisenoolithe in Nord-Australien. A. B. Edwards.

Bei den neuen Erforschungen wurden in Nordaustralien drei in flachem Wasser abgelagerte Eisenoolithschichtkomplexe entdeckt, von denen einer ins Perm, die beiden anderen ins Obere Proterozoikum zu stellen sind. Die permischen Schichten sind den oxydierten Chamositoolithen Südostenglands ähnlich, sie enthalten jedoch mehr detritischen Quarz und Feldspat.

Die beiden präkambrischen Schichten bestehen unterhalb der Verwitterungszone aus Hämatitoolithen, aus einer chamositähnlichen Substanz, die in einem Sideritzement liegt, und aus wohlgerundetem Quarz. Sie sind Sandsteinen mit einem chamositartigem Bindemittel zwischengelagert. In der Verwitterungszone ist der Siderit und der Chamosit mehr oder weniger vollständig durch Quarz ersetzt; die ursprüngliche Struktur ist dabei in Einzelheiten erhalten geblieben.

RÉSUMÉS

Les roches charnockitiques d'Australie. A. F. Wilson.

Description de la structure des environs des 7 régions charnockitiques connues en Australie et des systèmes principaux de roches que l'on rencontre. Cette description repose sur des analyses chimiques représentatives dont certaines sont nouvelles. Dans quelques régions, les roches de faciès granulitiques métamorphisées dominent; dans d'autres, des relictes de charnockite sont inclus dans les roches à faciès amphibolitiques. La plupart de ces régions avoisinant les zones de grands bouleversements on est porté à supposer que la texture bien connue propre à la plupart des charnockites provient de la conductivité calorique le long des glissements en grande profondeur, d'étirement ou bien d'effondrement de blocs archaïques.

La plupart des roches australiennes apparentées aux charnockites sont des roches métamorphiques. Les roches basiques sont presque toujours meta-magmatiques, beaucoup d'entr-elles sont fortement altérées. Les roches intermédiaires sont en partie meta-magmatiques, en plus grande partie cependant meta-sédimentaires, ou bien ce sont des Granulites basiques granitisées.

Beaucoup de roches d'aspect charnockite ont subi plusieurs métamorphoses.

Les roches orthopyroxéniques acides non métamorphisées forment d'importantes intrusions dans le complexe charnockitique du centre de l'Australie. Ces « Magmes » proviennent probablement de la palingénèse de roches dans un milieu dépourvu d'oxygène.

Le Précambrien du Nord Ouest de Queensland, Australie. E. K. Carter.

Les roches précambriennes qui vont probablement depuis l'aire Archaïque jusqu'au Protérozoïque, s'étendent dans le NW de Queensland sur une surface de 25 000 miles. On peut les diviser en 4 groupes séparés par de fortes discordances. L'histoire des roches archaïques est peu connue. Elles se composent probablement de laves acides métamorphisées, de micaschistes, gneiss et migmatites. Les couches du Protérozoïque inférieur font partie d'un orogène. La partie ancienne du Protérozoïque inférieur est riche en laves acides et basiques. Elle atteint une puissance de 4000 pieds et a été déformée par une pression EW. Il y a eu probablement des intrusions granitiques avant que la série supérieure du Protérozoïque inférieur se soit déposée. Cette série se compose en grande partie de sédiments. Ceux-là atteignent leur plus grande puissance dans l'W et le NW de la partie centrale de la montagne composée du plus profond Protérozoïque. Ces sédiments atteignent une puissance maximale d'au moins 40 000 pieds. Cette même série a été déformée lorsque la pression en direction EW s'est renouvelée; ce plissement était accompagné d'intrusions granitiques. Ce territoire est plus ou moins fortement plissé, cependant dans les parties occidentales des linéaments bien définis font défaut.

Les sédiments et laves du Protérozoïque supérieur ont été déposés surtout dans l'W et NW du territoire. Leur plissement est minimal, ou modéré le long des axes dirigés de W au NW.

Le Précambrien — non comprise la région dolomitique de Camooweal — couvre 25 000 miles carrées dans le NW de Camooweal. Des recherches systématiques y ont été effectuées dès 1950 par des groupes de collaborateurs du Commonwealth Bureau of Mineral Resources et du Geological Survey of Queensland.

La carte géologique à grande échelle était terminée en 1954. Des corrections

et des levées détaillées dans des régions d'intérêt économiqe, sont en cours. Des cartes de 1 à 253 440 sont en préparation, Carter et Brooks sont en train de rédiger un compte-rendu de cette région. On a laissé de côté le dolomie de Camooweal datant du Protérozoïque supérieur ou du Cambrien inférieur. Noakes (1956) a discuté la position stratigraphique et paléogéographique.

La reconstruction de l'histoire géologique de cette région se base sur des observations détaillées. Mais le matériel ne suffit pas pour donner une interprétation définitive, surtout les intrusions granitiques ne sont pas encore assez élucidées.

Faunes fossiles les plus anciennes du Sud de l'Australie. M. F. Glaessner.

Une révision des études connues sur les fossiles précambriens du Sud de l'Australie a montré que la présence de Radiolaires est possible, mais que, par contre, tous les autres restes ont été, par erreur, attribués à des animaux. Les trouvailles d'Arthropodes restent douteuses.

La faune des grés et quarzites du Cambrien inférieur d'Ediacara ne contient pas seulement des Méduses. De nouvelles recherches ont prouvé qu'on y trouve des formes analogues aux types de *Pteridinium* et *Rangea* de la série de Nama du Sud-Ouest de l'Afrique. On les considère maintenant comme apparentées aux *Pennatulacea* récentes. Dans ces mêmes couches on trouve également *Spriggina (Annelida),* probablement *Siphonophora* et 2 espèces nouvelles d'Invertébrés.

Ces dernières couches sont recouvertes d'une série contenant, sans aucun doute, des fossiles du Cambrien inférieur, depuis les calcaires á *Archaeocyatha,* jusqu'à la zone à Protolenus.

La faune d'Ediacara se compose uniquement d'organismes sans coquille. Elle diffère donc foncièrement de toutes les faunes cambriennes. C'est pour cela qu'on peut lui attribuer l'âge précambrien.

La chaîne montagneuse de Musgrave dans le Sud de l'Australie. R. C. Sprigg et R. B. Wilson.

Les éléments structuraux, qui caractérisent les prolongements les plus orientaux du bouclier occidental australien ont une direction dominante E—W. Cette aptitude a continuellement influencé et guidé durant toute la longue histoire de cette région, les orogénèses ultérieures et le développement géomorphologique. Il est probable que 2 zones anticlinales principales se sont formées dans cette direction E—W; elles se sont conservées jusqu'à aujourd'hui en chaînes de montagnes et monts insulaires. Des intrusions batholitiques caractérisent la zone sud, tandis que les roches affleurant dans la région plus au nord sont principalement meta-sédimentaires. La zone granitique présente une intense anomalie négative de Bouguer (— 150 Milligal) qui témoigne de grandes différences de densité entre les masses de granit à densité minime et les gneiss granitiques schisteux de la chaîne du nord.

L'épaisseur de la crôute terrestre doit être, localement extraordinairement grande, pour pouvoir supporter un tel poids non compensé. Cependant de profonds fossés, dans lesquels des sédiments du Protérozoïque supérieur et de l'Ordovicien sont conservés, limitent les deux bords de l'anomalie négative.

Structures périphériques, roches granitiques et cassures crustales dans le S. E. de l'Australie. E. S. Hills.

Discussion sur la structure et le développement de plusieurs structures périphériques dévoniennes dans le S. E. de l'Australie ainsi que sur des intrusions

granitiques qui y sont reliées et témoignent de l'existence de failles périphériques dans le S. E. de l'Australie. Le complex magmatique de Marysville renferme dans l'effondrement périphérique de l'Archeron des couches à poissons et plantes. Son diamètre est de 15 miles anglaises. Il se compose d'une lave acide d'une puissance de 6.000 pieds et en 2ème ordre d'Andésite et de Basalte. La plupart des gisements appartiennent au même groupe magmatique. Le magma fondamental est intermédiaire, il ressemble beaucoup aux dacites à Hypersthen de la région. Probablement son intrusion s'est produite en masse cunéiforme venant de l'Est.

Australie et terre de Gondwana. C. TEICHERT.

Les progrès des recherches géologiques faites dans l'ouest de l'Australie pendant les dernières 20 années ont amélioré nos connaissances de l'histoire géologique et ont montré l'importance tectonique des grands bassins sédimentaires situés au bord ouest du continent australien.

On connait 4 grands bassins, dénommés du nord au sud:

1. Bonaparte Gulf-Basin, auquel s'accole vers le sud le Ord Basin, 15.000 km²;
2. Canning Basin, environ 446.000 km²;
3. Carnarvon Basin, 116.000 km²;
4. Perth Basin, environ 20.000 km².

Un cinquième bassin, l'Eucla Basin à la côte méridionale est géologiquement peu important.

Les premiers bassins sont remplis de sédiments paléozoïques, mesozoïques et caenozoïques, dont la puissance pour chaque bassin atteint de 5.500 à 12.000 m. La plus grande partie des sédiments est d'origine marine et contient une riche faune. Dans le Carnarvon Basin la série des couches est presque totalement marine. Toutes les formations du Cambrien jusqu'au Tertiaire sont représentées et contiennent des faunes qui témoignent de relations en partie avec l'Europe et l'Asie, en partie avec le nord de l'Amérique.

L'analyse de la plateforme continentale et des régions océaniques limitrophes montre que les bassins se prolongent en forme de dépressions, au large du bord de cette plateforme. La présence de ces bassins, le caractère de leurs faunes prouvent l'existence d'une mer à l'ouest de l'Australie. Cette mer limite — au moins depuis l'Ordovicien — le continent australien vers l'ouest. De plus, la composition des faunes terrestres permet de conclure que depuis le paléozoïque supérieur l'Australie a toujours été un continent. S'il a existé quelque part une terre de Gondwana, l'Australie n'en a jamais fait partie.

Géographie du Sakmara. D. HILL.

Les données paléontologiques et stratigraphiques connues ont servi de base à la construction de cartes montrant l'extension de la mer sur les continents du Sakmara au Permien inférieur.

Le matériel est suffisamment authentique pour l'hémisphère N., (Sauf pour les Indes), pour permettre la construction de cartes exactes. L'étendue de l'inondation montre que le climat différait beaucoup du climat actuel; mais on ne peut assurer l'existence de périodes glaciaires sakmariennes. Dans les continents méridionaux et l'Inde la province biogéographique « Gondwana » rendait douteuse la corrélation avec le continent nordique, cependant on a des raisons de croire que les dépôts glaciaires de la terre de « Gondwana » sont en partie sakmariens. Les cartes montrent que les parties terrestres du pays de Gondwana ont été peu réduites et que la glaciation la plus importante (en dehors de l'Inde) forme une ceinture entre 40° et 20° de latitude sud.

N'ayant aucune donnée sur la formation du Sakmara dans l'Antarctique, il serait prématuré de reconstruire les zones climatiques qui pourraient servir de base à une reconstruction ou contrôle de la dérive des continents et de la migration du pôle.

Stratigraphie et micropaléontologie du Crétacé de l'Australie Occidentale. D. J. Belford.

Discussion de la répartition, des relations et des valeurs stratigraphiques des microfaunes (surtout Foraminifères) dans les dépôts du Crétacé Supérieur de l'Australie Occidentale. Remarques sur la paléogéographie et la paléoécologie.

Le Gearle Siltstone, le grès vert d'Alinga et peut être celui de Molecap ont été déposés pendant le Cénomanien-Turonien

Parmi les Foraminifères recueillis, les formes planctoniques *Globotruncana (Praeglobotruncana) stephani* subspp. et *G. helvetica* ont une valeur stratigraphique restreinte. Le calcaire de Gingin et la partie inférieure du Calcilutite de Toolonga ont été déposés pendant le Santonien. Ces couches contiennent les Crinoïdes du genre *Marsupites* et *Uintacrinus*, plusieurs espèces de *Globotruncana* et *Neoflabellina* de plus *Bolivinoïdes strigillata strigillata*. Les couches Santoniennes sont connues vers le nord jusque dans la région des anticlinaux du Warroora.

Le Calcilutite de Toolonga se continue jusqu'au Campanien inférieur, où, dans la faune, apparaît *Globotrunca arca*. Il n'est pas possible de prouver l'existence de gisement Campanien dans le Bassin de Perth, il est probable qu'une grande partie des sables verts de Poison Hill est de cet âge. D'après les Foraminifères le dépôt des Calcarenites de Korojon commença au Campanien. *Globotrunca arca*, *Cibicides voltziana* et *Bolivina incrassata* sont des espèces importantes.

Les couches supérieures des Calcarenites de Korojon et les marnes de Miria sont d'âge Maastrichtien. Les marnes de Miria contiennent les espèces *Globotruncana stuarti, G. citae* et *G. contusa*. Il est probable que la partie supérieure du grés vert de Poison Hill peut être placée dans le Maastrichtien.

Structure de la Nouvelle-Zélande d'après l'examen sismique. G. A. Eiby.

La région Nouvelle-Zélande est caractérisée par une croûte de 20—25 km d'épaisseur et une sous-croûte qui atteint une profondeur d'au moins 370 km. Ces deux croûtes sont séparées par une couche intermédiaire qui s'étend sur une profondeur d'environ 100 km. La croûte est divisée en blocs par des failles abruptes. Certains blocs sont encore en activité sismique, d'autres sont stables.

Cette région ist limitée à l'Est par le Bassin Pacifique, à l'Ouest par le Bassin Tasmanien qui possèdent une croûte océanique de 6 km. La croûte inférieure est traversée par une structure cunéiforme renfermant de profonds foyers sismiques. On l'a nommée la Sub-Crustal-Rift; elle est probablement un prolongement de la sismisité du fossé de Kermadec. Elle se dirige à peu près du Sud-Ouest de la Bay of Plenty jusqu'au Farewell Spit; puis elle prend brusquement la direction S. S. E. pour se terminer dans le voisinage des failles alpines (Alpine Fault). Les failles de direction N. O. und N. W. sont actuellement en activité. La faille-N. W., la plus importante, longe le détroit de Cook.

Il est probable que les failles principales se sont formées successivement au-dessus du Sub-Crustal-Rift. Les blocs stables ne sont pas si fracturés. La structure croustale paraît différente des deux côtés du Rift. A l'Ouest la croûte est plus puissante d'environ 5 km et contient une couche traversée par les ondes P avec une vitesse au-dessus de 7 m/sec. On n'a pas observé à

l'est du Rift de vitesses dépassant $6^1/_2$ km/sec. Il n'existe aucune indiquation sur une structure arquée. Toutes les structures croustales ou subcroustales paraissent être rectilignes.

Importance structurale de la formation du fond de la mer aux alentours de la Nouvelle-Zélande. J. W. Brodie.

Les hauteurs et profondeurs océaniques aux alentours de la Nouvelle-Zélande ont une direction linéaire accentuée. On peut les diviser en 3 groupes dirigés N.W., E.W. et N.N.E.—S.S.W. On les considère comme des provinces structurales, nommées Provinces du N.W., de Chatham et de Kermadec. Elles diffèrent entr'elles tant par l'âge que par la Géographie. La terre de Nouvelle-Zélande se trouve juste là où 3 groupes structurals se rencontrent. On croit voir dans ce fait l'origine du relief.

On n'a pas observé de signes d'une activité caenozoïque dans les structures appartenant aux provinces du N.W. et de Chatham. Le relief submarin est sans doute d'âge prétertiaire.

Des mouvements se sont produits dans la structure de la Province de Kermadec jusqu'à la période actuelle.

La formation sous-marine de cette région est considérablement plus jeune que dans les autres provinces.

Oolithes ferrugineux dans le nord de l'Australie. A. B. Edwards.

Les dernières recherches faites dans le nord de l'Australie ont mis à jour 3 complexes de couches d'oolithes ferrugineux déposés dans une eau peu profonde.

L'une est d'âge permien, les 2 autres appartiennent au Protérozoïque supérieur. Les couches permiennes ressemblent aux oolithes chamositiques oxydées du sud de l'Angleterre. Elles contiennent cependant plus de Quartz détritique et de Feldspat.

Les deux couches précambriennes sont formées — en dessous de la zone de décomposition — d'oolithes d'Oligiste, d'une substance chamositique englobée dans un ciment de Siderit et de Quartz arrondi.

Elles sont intercalées entre des grès cimentés par une sorte de Chamosit. Dans la zone de décomposition, Siderit et Chamosit sont plus ou moins remplacés par le Quartz, la structure primaire est cependant conservée dans tous ses détails.

РЕЗЮМЕ

Чарнокитовые породы Австралии. А. Ф. Вильзон.

Описывается структура окрестности 7 известных чарнокитовых областей Австралии и главные в них встречающиеся типы пород. Изложение опирается на репрезентативные химические анализы, часть которых являются новыми.

В некоторых областях преобладают породы метаморфной гранулитной фации, в других чарнокиты появляют как реликты в породах амфиболитовой фации. Близость большинства областей к большим зонам разрушений даёт предположение, что хорошо известная, свойственная большинству чарнокитов возникла либо проводом тепла вдоль глубоких надвигов и зон срезании или опусканием частей первичных пород в более теплые зоны вдоль сбросов.

Большинство пород близких чарнокитам возникли в результате метаморфизма. Основные породы по большей части метамагматичны, многие из них были метаморфозом очень изменены. Средние породы — частично метамагматические, но б. ч. — осадочные, или рассматриваются гранитизированными основными гранулитами. Много пород, являющиеся теперь чарнокитами, подвергались нескольким метаморфозам. Неметаморфные кислые ортопироксеновые породы образуют значительные интрузии в чарнокитовых комплексах центральной Австралии. Эти „магмы" вероятно возникли палингеническим расплавлением метаморфных пород в безкислородной среде.

Докембрий северозападного Квинсленда (Австралия). Е. К. Картер.

Докембрийские горные породы от вероятного архея до верхнего протерозоя выходят на поверхность в сев.-зап. Квинсленде на территории 25.000 квадратных миль. Их можно разделить на 4 большие группы, разделенной резкими несогласиями. О истории архейских пород известно очень мало. Они вероятно охватывают превращённые кислые лавы, слюдистые сланцы, гнейсы и мигматиты. Слои нижнего протерозоя являются частью орогена. Самый нижный протерозой обилен кислыми и основными лавами; наибольшая мощность его составляет не менее 40.000 фут и он сильно деформирован сжатием широтного направления. Возможно была интрузия гранитов до отложения толщи нижнего протерозоя, состоящего б. ч. из осадочных пород. Эти осадочные породы достигают своей наибольшей мощности к западу и северо-западу от горного ядра, сложенного из самого древнего протерозоя, но охватывают и самый древный протерозой. Складчатость — сильная до умеренной, однако к западу от области выходов хорошо выявленные линейные элементы отсутствуют.

Отложение осадков и лав верхнего протерозойкого возраста главным образом произошло в западной и северо-западной частях области. Они слабо до умеренного складчаты с простиранием осей западного до северозападного направления.

Докембрий северозападного Квинсленда выходит на поверхность на территории в 25.000 квадратных миль, не включая доломит Кэмувил. К систематической полевой работе приступили в 1950 г. комплексная группа работников Комменвельс бюро минеральных запасов и Геологическая служба Квинсленда.

Обзорное картирование области было закончено в 1954 г. Обработка и детальная съемка интересных в хозяйственном отношении областей еще ведутся. Подготовляются карты в масштабе 1 : 253.440, и вырабатывается отчёт о этой области (Картер и Брукс, в подготовке), не включая верхнепротерозойский или нижнекембрийский доломит Кэмувил. Его стратиграфическое и палеогеографическое положение обсуждается Ноксом (1956 г.).

Резюме

Реконструкция геологического развития этой области является толкованием наблюдавшихся деталей. Факты еще не достаточно совершены, чтобы дать возможность законченной интерпретации развития области, охватывающей все точки зрения. Особенно интрузии гранитов еще не полностью расшифрованы.

Самые древние ископаемые фауны Ю. Австралии. М. Ф. Глеснер.

Критический обзор известных данных о докембрийских ископаемых Ю. Австралии приводит к выводу, что существование радиолярий возможно, но однако объяснение всех остатков из докембрийских слоев как органических, были ошибочны. Утверждение о существовании членистоногих недоказано.

Описанная Шприггом фауна из раннекембрийского песчаника и кварцита Эдиакара содержит не только медузы. Новые исследования доказали, что в них встречаются и формы, имеющие сходство с типами Pteridinium и Rangea из серии Нама югозападной Африки. Теперь их считают родственными современных Pennatulacea. В тех-же слоях существуют и Spriggina (Annelida), вероятно Siphonophara и два совершенно новых типа беспозвоночных.

Слои с этой фауной перекрываются толщой без сомнении нижнекембрийских ископаемых (от археоциатитовых известняков до зоны с Protolenus). Так как фауна Эдиакара, составщая только из организмов без раковины, в корне от всех известных кембрийских фаун, то ей можно приписать ещё докембрийский возраст.

Горная цепь Масгрейв в Ю. Австралии. Р. К. Шпригг и Р. В. Вилзон.

Структурные элементы самых восточных отрогов зап. австралийского щита имеют преобладающее широтное простирание. Эта обстановка постоянно определяла и направляла последующие горообразовательные движения и геоморфологическое развитие области во время её длительной истории. Вероятно в этом широтном направлении образовались две главные антиклинальные зоны. Они сохранились до настоящего времени ввиде горных цепей и останцев. Более южная зона характеризуется громадными батолитными интрузиями, в то время как более северная зона преимущественно метаосадочными породами. Зона гранитов показывает сильную отрицательную аномалию Бугэ (— 150 миллигал), указывающую на большую разницу плотности между массовыми гранитами меньшей плотности и сланцеватыми гранитовыми грейзенами северных цепей. Мощность земной коры должна быть местами чрезвычайно велика, чтобы выдерживать такой некомпенсированный груз. Однако глубокие грабены, содержащие осадки верхнего протерозоя и ордовика, ограничивают оба края отрицательной аномалии.

Кольцевые структуры, гранитовые породы и нарушения земной коры в юго-восточной Австралии. Э. С. Хиллс.

Обсуждается структура и развитие некоторых девонских кольцевых структур и связанные с ними гранитовые интрузии, указывающие на существование кольцевых нарушений в глубине ю.-в. Австралии. Магматический комплекс Мэрисвилл содержит в котловинообразном обвале слои содержащие остатки рыб и растений. Его поперечник — 15 миль, он содержит кислые лавы мощностью 6.000 фут; в незначительной мере встречаются андезиты и базальты. Большинство пород принадлежает к одной магматической группе. Первозданная магма имеет средный состав и очень схожа с гиперстеновыми дацитами этой области. Магма вероятно внедрилась как магматический клин с востока.

Австралия и Земля Гондвана. К. Тейхерт.

Успехи геологического исследования западной Австралии последных 20 лет привели к лучшему познанию геологической истории и тектонического значения обширных осадочных бассейнов, находящихся на западном краю австралийского материка. Известны 4 обширных бассейна, которые в настоящее время имеют следующие названия (от севера на юг): 1. Бассейн

зал. Бонапарте с более древным южным смежным образованием — бассейн Орд, 15.000 км²; 2. Бассейн Кэннинг, 446.000 км²; 3. Бассейн Карнарвон, 116.000 км²; 4. Бассейн Перс, около 20.000 км². Пятый бассейн — бассейн Оикла, на южном берегу, имеет лишь небольшое геологическое значение. Первые четыре бассейна наполнены палеозойскими, мезозойскими и кенозойскими отложениями, общая мощность которых в отдельных бассейнах составляет 5.500—12.000 м. Во всех бассейнах морские отложения с обильными ископаемыми составляют главную часть осадочных масс. В бассейне Карнарвон даже почти вся толща морская. Представлены все геологические формации от кембрийской до третичной; они содержат фауны, показывающие связь частично с Европой и Азией, частично с С. Америкой. Анализ материкового шельфа и смежных океанских областей показывает, что бассейны можно наблюдать ввиде депрессии выходящей за пределы шельфа. Наличие бассейнов, а также характер их осадков и состав фаун указывают на существование моря в западной части Австралии, которое австралийский материк к западу отграничило по меньшей мере с ордовикского времени. Кроме того беспрерывность материка Австралии со времени нижнего палеозоя явствует из состава наземных фаун. В случае действительного существования в каком либо виде Земли Гондваны, то Австралия никогда не принадлежала к ней.

География сакмарского яруса. Д. Хилл.

Автор использовал известные палеонтологические и стратиграфические данные как основу для составления карт, показывающих в каком размере континенты в сакмарском ярусе (нижный перм) покрыты были морем. Для северного полушария, кроме Индии, данные являются достаточно надёжными, чтобы составить относительно точные карты. Размер морского покрытия указывает на то, что климат сакмарского яруса значительно отличался от современного; но несомненные сакмарские ледниковые периоды не встречаются. В южных материках и в Индии биогеографическая провинция „Гондвана" вызвала сомнение в её корреляции с северными материками, но имеются основания предполагать, что ледниковые отложения Земли „Гондваны", по крайней мере частично, являются сакмарского возраста. Карты показывают, что материковая территория Земли „Гондваны" была только немного редуцирована и, что главные ледниковые периоды (кроме в Индии) появлялись в поясе между 40° и 20° южной широты. Из-за еще отсутствующих знаний о характере сакмарского яруса в Антарктике, реконструкция климатических зон, позволяющих установление или проверка гипотез перемещения материков и полюсов, является в настоящее время еще слишком рискованной.

Стратиграфия и микропалеонтология верхнего мела Зап. Австралии. Д. Ж. Бельфорд.

В статье обсуждается распределение, взаимоотношения и стратиграфическое значение микрофаун (главным образом фораминиферов) в верхнемеловых отложениях Зап. Австралии; кроме того рассматриваются палеогеография и палеоэкология.

В сеномане отложились алевролитовая порода Гэрл, зеленый песок Алинта и, может быть, зеленый песок Молекэп. Среди найденных фораминиферов появляются планктонные формы Globotruncana (Praeglobotruncana) stephani subsp. и g. helvetica, которые являются в стратиграфическом отношении ограничными.

Отложение известняка Гингин и нижней части кальцилутита Гоолонга произошло во время сантона. Эти слои содержат роды криноидей Marsupites и Uintacrinus, многие разновидности Globotruncana и Neoflabellina и кроме того Bolivinoides strigillata strigillata. Сантонские слои известны к северу в выходах вплоть до области антиклинали Варроора.

Кальцитулит Тоолонга восходит до нижнего кампана, здесь появляет Globotruncana arca. Доказать наличие кампана в бассейне Перс невозможно; возможно что большая часть зелёного песка Пойзен Хилл имеет этот возраст. По фораминиферам следует, что отложения кальцаренита

Короджон началось в кампанское время. Главные разновидности **Globotruncana arca, Cibicides voltziana** и **Bolivina incrassata.**

Верхние слои кальцарената Короджон и мергеля Мирия имеют маастрихтский возраст. Мергель Мирия содержит и заключает в себе **Globotruncana stuarti, G. citae** и **G. contusa.** Верхняя часть зелёного песка Пойзен Хилл повидимому надо отнести к маастрихтскому ярусу.

Структура Новой Зеландии по сейсмическим исследованиям. Г. А. Эйбы.

Область Новой Зеландии характеризуется земной коры мощностью 20—25 км и субкорой до глубины 370 км. Эти земные коры отделены друг от друга промежуточным слоем, протягивающимся до глубины примерно 100 км. Земная кора разделена в глыбы круто падающими сбросами. Несколько глыб — сейсмически активны, другие — стабильны.

К востоку область ограничивается тихоокеанским бассейном, к западу — тасманским. Мощность океанических кор в этих двух регионах составляет 6 км.

Клинообразная структура, т. н. субкоровый рифт, в которой сосредоточена глубокофокусная сейсмичность, пересекает субкору и является, вероятно, продолжением сейсмичности грабена Кермадек. Структура проходит примерно в ю.-з. направлении от залива Пленти до Фэрвелл Спит; где она внезапно поворачивает в ю.-ю.-в. направление и заканчивается вблизи альпийского сброса (Alpine **Fault**). Сбросы, простирающиеся в с.-в. и с.-з. направлении, ныне являются активными. Важнейший сброс с.-з. простирания проходит через прол. Кука.

Можно предполагать, что главные сбросы образовались последовательным залеганием над субкоровым рифтом. Таким образом устойчивые глыбы не были разбиты. Структура коры обейх сторон вероятно различна. На западе мощность земной коры прибл. на 5 км больше, и в коре имеется слой со скоростью волн-Р свыше 7 км/сек. Скорости более $6^1/_2$ км/сек. на востоке не наблюдались. Нет указаний о дуговой форме структуры. Все структуры коры и субкоры повидимому прямолинейны.

Структурное значение образования морского дна. И. В. Броди.

Положительные и отрицательные формы рельефа океанского дна вокруг Новой Зеландии ясно показывают линейное простирание. Разделяются они на три группы, главные структуры которых имеют с.-з., широтное и с.-с.-в. простирание. Эти группы рассматриваются как структурные провинции: северозападная провинция, провинция Шэтэм и Кермадек, различающиеся как по возрасту так и по географии. Земная масса Новой Зеландии находится на том месте, где эти три структурные линии встречаются, и считают, что рельеф обусловлен этим объединением.

Признаки новой деятельности в структурах, принадлежащих к северозападной провинции и провинции Шэтэм не наблюдаются. Подводный рельеф вероятно дотретичного возраста.

Движения имели место в структуре провинции Кермадек вплоть до настоящего времени. Подводное образование этой области гораздо моложе.

Железные оолиты Сев. Австралии. А. В. Эдвардс.

В результате новых исследований в Сев. Австралии открыты три железооолитовых толщи мелководного происхождения, одна из которых имеет пермский возраст, две другие — верхнепротерозойский. Пермские слои имеют сходство с окисленными шамозитовыми оолитами ю.-в. Англии, но содержат большее количество детритового кварца и полевого шпата.

Оба докембрийских слоя ниже зоны выветривания состоят из гематитовых оолитов, из шамозитообразного вещества, находящегося в сидеритовом цементе, и из хорошо окатанного кварца. Они являются прослоями в песчаниках с шамозитообразным связующим цементом. В зоне выветривания сидерит и шамозит более или менее совершенно замещались кварцем при детальном сохранением первоначальной структуры.

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